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CRF AEROMECHANICS PRIMER

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WRIGHT PATTERSON AFB OH 45433-7251

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FINAL REPORT

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THE CRF AEROMECHANICS PRIMER IS A TECHNICAL DESCRIPTION OF THE FACILITY'S AEROMECHANICS STATION AND A REVIEW OF BASIC AEROMECHANICS PRINCIPLES. THE PRIMER WILL SERVE AS A GUIDE FOR PRESENT AND FUTURE AEROMECHANICAL MONITORS AS IT DEFINES HOW TO OPERATE THE MONITORING STATION IN SUPPORT OF CRF COMPRESSOR TESTING.

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FOREWORD

The purpose of this report is to explain the role of aeromechanics in support of test programs in the Compressor Research Facility at WPAFB, and to provide aeromechanical engineers/monitors with some guidelines for conducting aeromechanical test programs effectively and knowledgeably. Much of the information herein comes from the author's experience in aeromechanics, his association with the Compressor Research Facility, and from the references cited in Section 5.0.

The author would like to acknowledge the valuable assistance of Richard C. Taylor with the technical aspects of the instrumentation discussions.

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GLOSSARY OF SOME AEROMECHANICAL TERMS

aeromechanics: A physical science dealing with energy and forces pertaining to the equilibrium, deformation, and/or motion of solid bodies immersed in air.

amplitude: The maximum value of a periodically varying quantity, usually measured from its equilibrium value taken as zero. This is called the "zero-to-peak amplitude" or simply the "single amplitude." Aeromechanics mostly deals with the peak-to-peak amplitude, which is twice the single amplitude, and is referred to as the "double amplitude."

Campbell diagram: A plot of frequency versus rotor speed with natural vibratory frequencies and excitation frequencies (engine order lines, or per-rev lines) for rotating machinery. Intersections of engine orders and natural frequencies define rotor speeds which can result in resonant vibration. This can also be a plot of frequency versus time.

data acquisition: The recording of experimental data, either by analog or digital means, occurring during a component test.

data reduction: Post-test processing of the experimental data to better interpret the events which occurred during the test.

engine strain gage: A strain gage applied to turboblading to measure the stress during the test vehicle operation. Sometimes called an engine gage.

flutter: The unstable condition where the vibratory motion of the blade creates changes in the aerodynamic loading on the blade such that the loading is in phase with the blade motion and thereby increases the amplitude of the blade vibration. This is also called self-excited vibration or aeroelastic instability. This type of blade response usually is a non-integral (does not correspond to a particular engine order) vibration.

forced vibration: Any vibration caused by external excitation. This response can become large as the excitation frequency approaches the natural frequency of the blade, i.e., a resonance.

frequency spectrum: A graphical display of the amplitude distribution of the periodic signal as a function of frequency.

high-cycle fatigue: The failure of a material as a result of large numbers of cycles (>10 E6 cycles) of vibratory strain which exceeds the elastic limit of the material.

GLOSSARY (Continued)

instability: See flutter.

Kulite: A brand name for a high-response pressure transducer which has been used with such frequency that it's name is a synonym for this kind of transducer.

light probe: A non-interference device that uses light reflected from the blade tips for measuring the blade deflection.

limit-cycle: The state of blade flutter where the forces causing the self-excited vibration are in equilibrium with the blade's internal restoring forces, thus limiting the vibratory amplitude from increasing further. (Perhaps the term limit-amplitude would be more descriptive.)

low-cycle fatigue: The failure of a material as a result of a low number of cycles (<10 E4 cycles) of vibratory strain which exceeds the plastic limit of the material.

mode shape: The characteristic vibratory deflection distribution for a body vibrating at a natural frequency.

modulation: The amount of variation, primarily in amplitude, of a vibratory signal.

node line: A line through the mode shape where the deflection is zero.

resonance: See forced response.

rotating stall: Local breakdown of flow in the cascade. These stall pockets rotate at approximately one-half the rotational speed of the rotor.

separated flow vibration: Blade vibration caused by turbulent flow resulting from separation of the boundary layer on the blade surface. This is characterized by random amplitude modulation and typically occurs as the stage is throttled toward the stall boundary.

slip ring: A rotating electro-mechanical device with brushes and commutators for transmitting electrical signals from rotating instrumentation to non-rotating data acquisition and processing equipment.

stall: The loss of aerodynamic loading that results when flow separation occurs due to insufficient velocity or excessive blade incidence angle.

GLOSSARY (Concluded)

strain gage: A device that uses the change of electrical resistance of a wire under strain to measure the stress amplitude of the structure to which it is attached.

turboblading: Any turbomachinery blading, either rotating or not.

ABBREVIATIONS AND ACRONYMS

Accel	Acceleration
A/M	Aeromechanics
ATDS	Analog Tape Digitizing System
BPR	Bypass ratio
BPV	Bypass valve
CD	Campbell diagram
CDV	Core discharge valve
CRF	Compressor Research Facility
da	Double amplitude (or peak-to-peak)
Decel	Deceleration
DRU	Data Reduction Unit
DV	Discharge valve
EO	Engine Order (1/rev, 2/rev, ..., etc.)
FFT	Fast Fourier transform
FOD	Foreign object damage
HCF	High-cycle fatigue
HOL	High operating line
IGV	Inlet guide vane
ips	Inches per second
IRIG	International Range Instrumentation Group

ABBREVIATIONS AND ACRONYMS (Concluded)

ksi	Kilopounds per square inch
LCF	Low-cycle fatigue
LE	Leading edge
LOL	Low operating line
n/rev	Nth engine order (n per rev)
NOL	Nominal operating line
Nc	Corrected speed
Np	Physical speed
OGV	Outlet guide vane
rpm	Revolutions per minute
sa	Single amplitude (or zero-to-peak)
SFV	Separated flow vibration
S/G	Strain gage
SGMS	Strain Gage Monitoring System
SL	Scope limit
TCASM	Two Channel Alarm Sensing Module
TE	Trailing edge
1F	First flexural mode of vibration
1T	First torsional mode of vibration
1-2S	First two-stripe mode of vibration

1.0 INTRODUCTION

Aeromechanics (A/M) support of test programs in the Compressor Research Facility (CRF) can be broken into three functions: test preparation, test monitoring, and post-test data analysis and reporting. Figure 1.1 shows this A/M support relative to other groups. CRF A/M testing is conducted in support of engine technology development programs. Such testing is usually performed with aerodynamic data acquisition and performance mapping. During these tests, the goal of A/M, in a word, is to make sure that the monitored sensors stay within acceptable levels. High stress events can be accidental or on purpose, if this kind of testing is required, so the A/M leader and monitors now must ensure that over-stress failures within the test vehicle do not occur.

The dynamic strain gages (S/G's) are the means by which the A/M monitor evaluates the mechanical behavior of the test article. The signals from these S/G's are displayed on oscilloscopes (simply called scopes) which the A/M monitor carefully watches and assesses their levels with respect to their operating limits, i.e., scope limits. The simultaneous observation and interpretation of S/G signals from many blades in several stages of a compressor can be difficult for an A/M monitor. This task includes the identification of the type of vibration, the interpretation and assessment of safety level relative to established limits, and also to direct a change in operating conditions to avoid failure and/or provide direction for optimizing the aerodynamic performance of the compressor. In the CRF, this is made somewhat easier by the Strain Gage Monitoring System (SGMS), see Section 3.3.6, which can monitor up to 108 channels of data.

1.1 AEROMECHANICS MONITOR

The aeromechanics monitor is sometimes referred to as a stress monitor because the S/G, i.e., the stress, is the primary means of identifying the vibratory condition and ensuring that the mechanical integrity of the test article is maintained. Often, more than S/G's are to be monitored, e.g., light probes, accelerometers, or Kulites. For this reason, the term aeromechanics monitor seems more appropriate and will be used hereinafter.

1.2 CRF AEROMECHANICAL TEST OBJECTIVES

Testing in the CRF is conducted in support of engine/component technology development programs. To this end, the A/M objectives include:

Ensuring test article safe operation,
Verifying analytical blade frequencies and stresses,
Avoiding resonances which cause excessive stresses,
Avoiding regions of instability, and
Acquiring adequate test data to satisfy the contractor stated objectives.

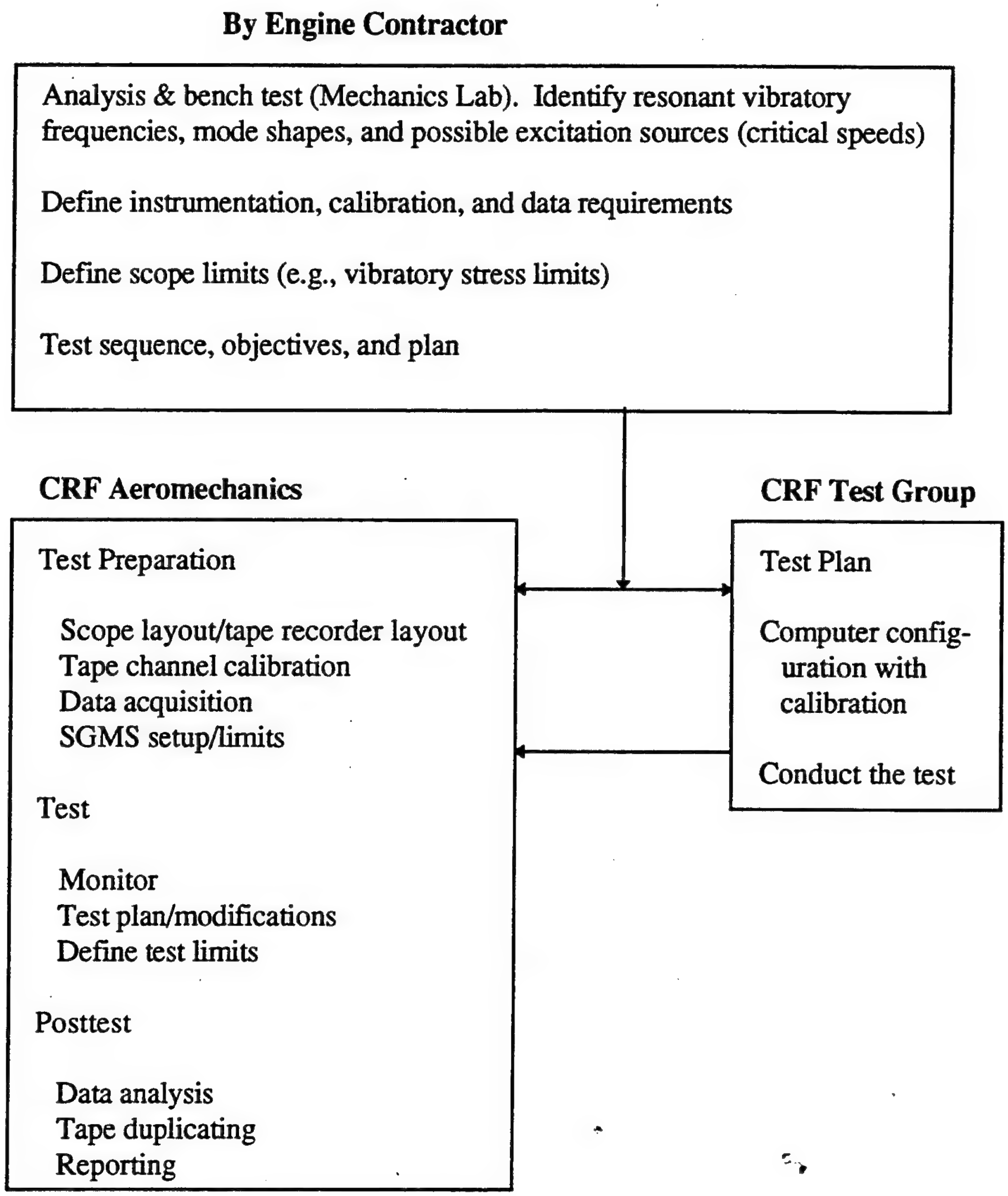


Figure 1.1. Aeromechanics Support of CRF Tests.

2.0 PREPARATION FOR THE TEST PROGRAM

2.1 OBJECTIVES

From the aeromechanical standpoint, the goals to be achieved by the subject investigation and the role of aeromechanical inputs must be adequately and completely defined. Some examples are:

a. Ascertain the cause of aeromechanical problems, and identify possible solutions.
b. Evaluate fixes for aeromechanical problems.
c. By aeromechanical means, provide safety from possible fatigue failures of the blading.
d. Certify/qualify aeromechanical adequacy of blading for contractual commitments.
e. Supply insights into aerodynamic characteristics through aeromechanical observations.

2.2 TEST PLAN

The Test Plan should be reviewed by CRF A/M to ensure that proper aeromechanical procedures are followed. The following guidelines apply to the overall test plan:

a. The scope of investigation must be adequate to achieve the desired aeromechanical goals, based on the above role of aeromechanics in the investigation.
b. The sequence of testing should balance acquisition of the most critical data against the possibility of premature fatigue failure, as well as loss of instrumentation coverage. Some general guidelines are:
* Obtain data to top speed as early in the test as practical,
* For the first time to top speed, keep operation between the nominal operating line (NOL) and low operating line (LOL) pressure ratios to avoid unusual and possibly dangerous aeromechanical conditions such as stall, flutter, or excessive blade or vane passing resonant excitation due to severe cascade loading, and
* Take stalls in low-to-high speed sequence to avoid encountering a possible show stopping violent stall at high speed. Preview of this can be realized by observing the progression of stall stresses with speed.

2.3 SCOPE LIMITS

Scope limits must be calculated by the contractor and provided to CRF A/M for all modes up to blade/vane passing frequencies and for the range of operating conditions to be encountered during the test program. The scope limits should be obtained from the engine contractor as early as possible so that the SGMS alarm and warning levels can be programmed.

2.4 TEST MONITORING

Details of test monitoring needs are discussed in Chapter 3.0. With respect to preparations for testing, the watchword is timeliness, as well as attention to details.

Information for scope setup, calibration, tape recording layouts and speeds, and slip ring hookup, must be established as early as possible to facilitate implementation at the A/M station.

3.0 CONDUCTING THE TEST PROGRAM

Aeromechanical aspects of test programs are critical from the standpoint of both immediate and long range test article safety, as well as in supplying insights into aerodynamic characteristics of the machine. Details are supplied in the following sections which are intended to maximize the effectiveness of the aeromechanics monitors involved in such test programs.

3.1 RESPONSIBILITIES OF THE AEROMECHANICS LEADER

a. His Identity -- The aeromechanical leadership takes several possible forms:

* He may be one person, separate from the primary A/M monitors, who consolidates their aeromechanical information into an overall interpretation of the test article aeromechanical characteristics. This data is then entered in the Test Run Summary and may be passed on to pertinent personnel.
* He may be one of the primary A/M monitors, interpreting his own aeromechanical information along with that of the other monitors for saving and transmittal if needed.
* His responsibilities may be shared by some, or all, of the A/M monitors, each providing his own aeromechanical conclusions.

b. Preparations for the Test Program -- The A/M leader is responsible for making sure that all aeromechanical aspects of the program are complete and accurate prior to the scheduled initiation date of the program. The items, to which he either contributes or is responsible for, are:

* Completed test plan,
* Monitoring needs -- both technical and personnel aspects,
* Data recording needs,
* Agreement as to operational procedures and ground rules,
* Scope limits,
* The warning and alarm limits in the SGMS, and
* Supply log sheets and other forms needed for data analysis and data summary during the test program.

c. Safety of Operation -- Contributions to assurance of test article safety through interpretation of monitored and/or play-back stress signals during the test.

d. Aerodynamic Implications -- Interpretation of monitored signals for aerodynamic implications, and potential aeromechanical problem areas in other environments than those involved in the subject test program.

e. Guidance of Others -- Provide assistance, coaching, and technical guidance to A/M monitors as required to maximize their monitoring effectiveness.

f. Instrumentation Changes -- During the test program, maintain a log of instrumentation losses, and define and log any revised circuitry hookups, monitoring scope modifications, and tape recorder channel changes.

g. Interim Data Analysis -- He is responsible for interim stress data analysis, summaries, and cumulative fatigue damage estimates (if applicable) during the test program.

h. Feedback -- During the test program, he provides authoritative feedback on aeromechanical aspects to the CRF manager and the Test Director.

i. Analysis and Documentation -- Following completion of the test program, he conducts necessary data analysis, or gathers it from others responsible for certain aspects of the program, and documents the aeromechanical characteristics, implications, conclusions, and recommendations based on this information.

3.2 THE AEROMECHANICS MONITOR

The A/M monitor's primary tasks include:

a. The singularly most important task is the taking of on-line test notes. On-line notes are required during all aeromechanically significant parts of any instrumented turbomachinery testing. These log sheets must be detailed enough so that the test sequence can accurately be reconstructed by someone besides the A/M monitor.

b. Insuring the test article safety and, if necessary, by superseding the control and returning the vehicle to a predetermined safe operating point. At each CRF A/M monitoring station, this is accomplished with the surge recovery button which opens the DV to the agreed upon safe operating point -- typically the LOL.

c. Having a sense of the aerodynamic characteristics of the test vehicle and their sensitivities to the test variables.

3.3 INSTRUMENTATION, MONITORING, AND RECORDING PREPARATIONS

This aspect of aeromechanical investigations is critical for immediate test article safety and aerodynamic insights, as well as to assure that recorded data are adequate for any desired post-test data reduction. In preparing for a test program, the aeromechanical engineer should be aware of the intent of each piece of instrumentation to facilitate the monitoring and recording of the data, and to identify the best techniques and arrangements for doing this.

3.3.1 Details of the CRF Aeromechanics Station

Knowledge is required of the procedures, monitoring setup, and recording capabilities at the CRF. A layout of the control room is shown in Figure 3.1. The portion of the control room relegated to the A/M station is shown in Figure 3.2 with the components delineated. A photo of a typical A/M monitoring station is shown in Figure 3.3. There are four A/M monitoring stations each with 36 oscilloscopes, a Spectral Dynamics spectrum analyzer, and a Nicolet digital oscilloscope. The A/M station has four 28-channel analog tape recorders and five 14-channel tape recorders. These nine recorders are permanent, but when the need arises, additional temporary recorders can be added. Too, there is the Strain Gage Monitoring System (SGMS) for 108 channels of data (see Section 3.3.6)-- the first three A/M monitoring station's signals are automatically input into the SGMS. There is also the Analog Tape Digitizing System (ATDS) which enables on-line Campbell diagrams to be obtained. There is also a 16-channel lightbeam oscillograph in the A/M station for online recording of waveforms on light sensitive paper. In addition, a hard copy printer is there which accepts data from each of the four Spectral Dynamics signal analyzers. A digital counter at each A/M monitor station uses the 6/rev signal to calculate and display the mechanical speed of the vehicle.

3.3.2 Aeromechanical Instrumentation Path

From the test article, the signals run to the 2nd floor Signal Conditioning Room in Building 20A. Here, 300 signal conditioning amplifiers are available to condition the data. The amplified signals are then sent to the A/M station in the CRF Control Room. The signals pass through buffer amplifiers before terminating in the A/M patch panel. With the proper patching, the signals are sent to the designated scope and tape recorder channel. The layout of this patch panel is shown in Figure 3.4.

3.3.3 Oscilloscope Display Details

a. Arrangement of Channels -- Since test article safety often requires rapid remedial action, scopes should be arranged to facilitate quick recognition and evaluation of potential problems. Some suggestions for the organization of strain gage scope displays are:

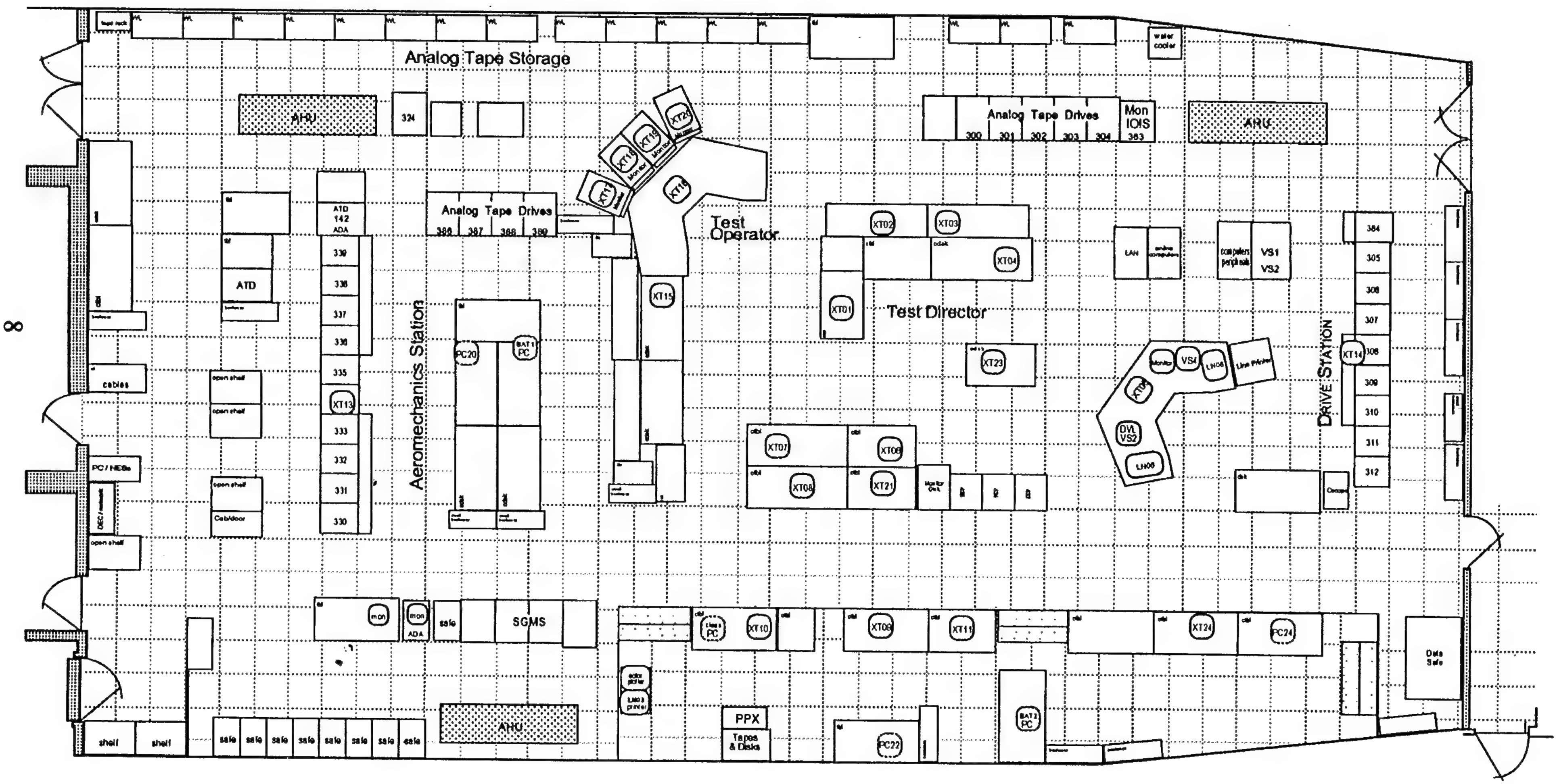


Figure 3.1. CRF Control Room.

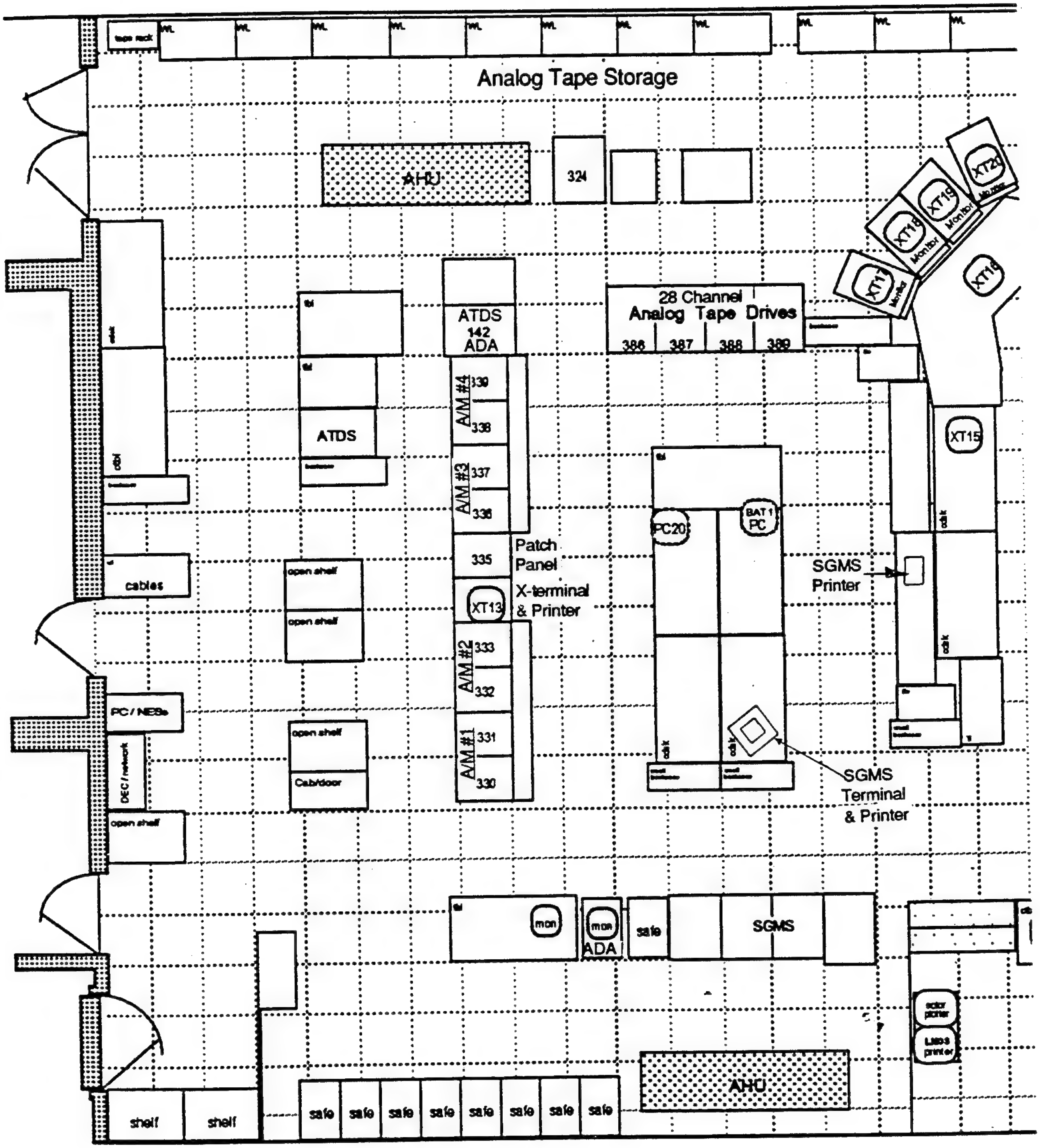


Figure 3.2. Aeromechanics Station.

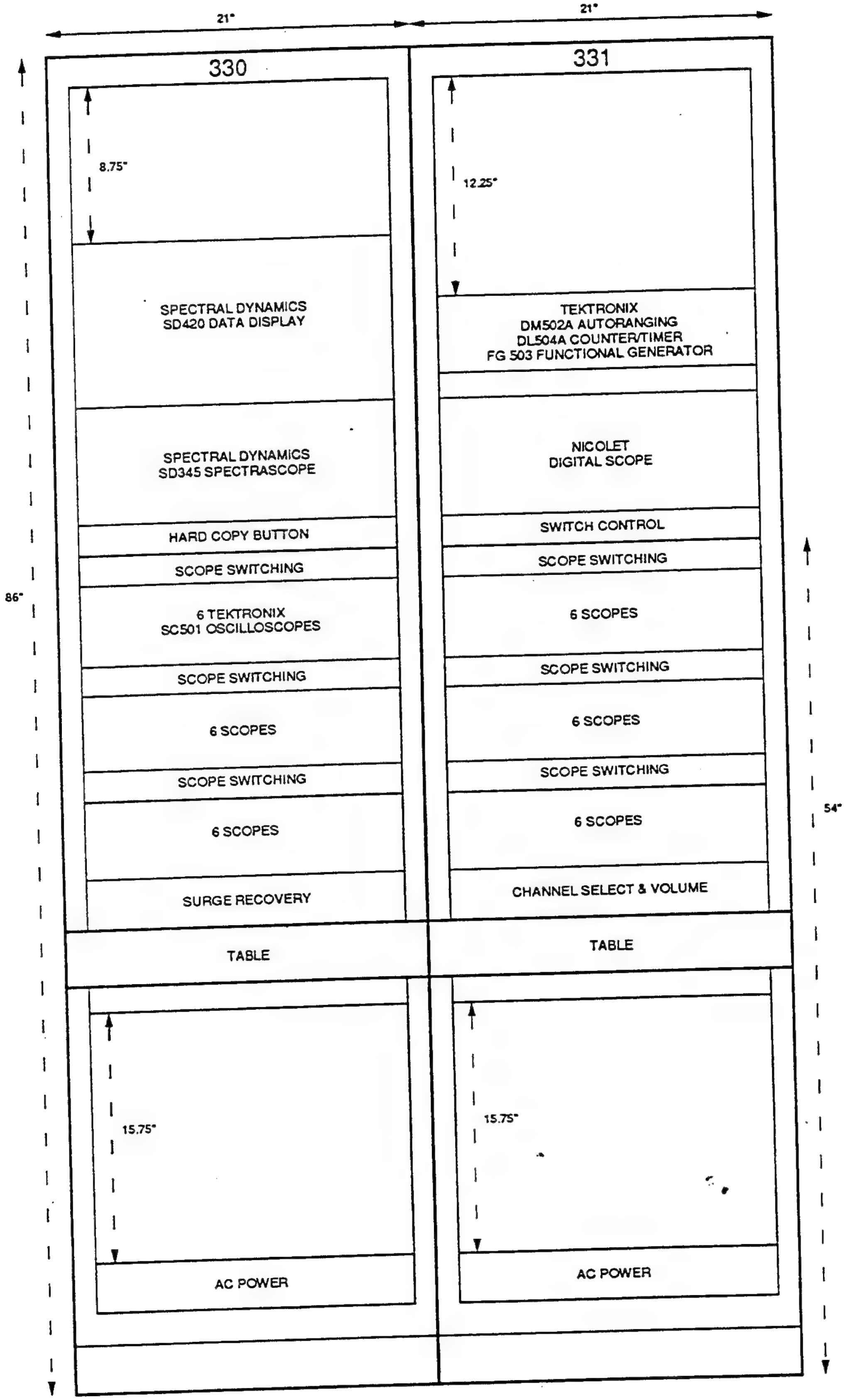


Figure 3.3. Typical Aeromechanics Monitoring Station.

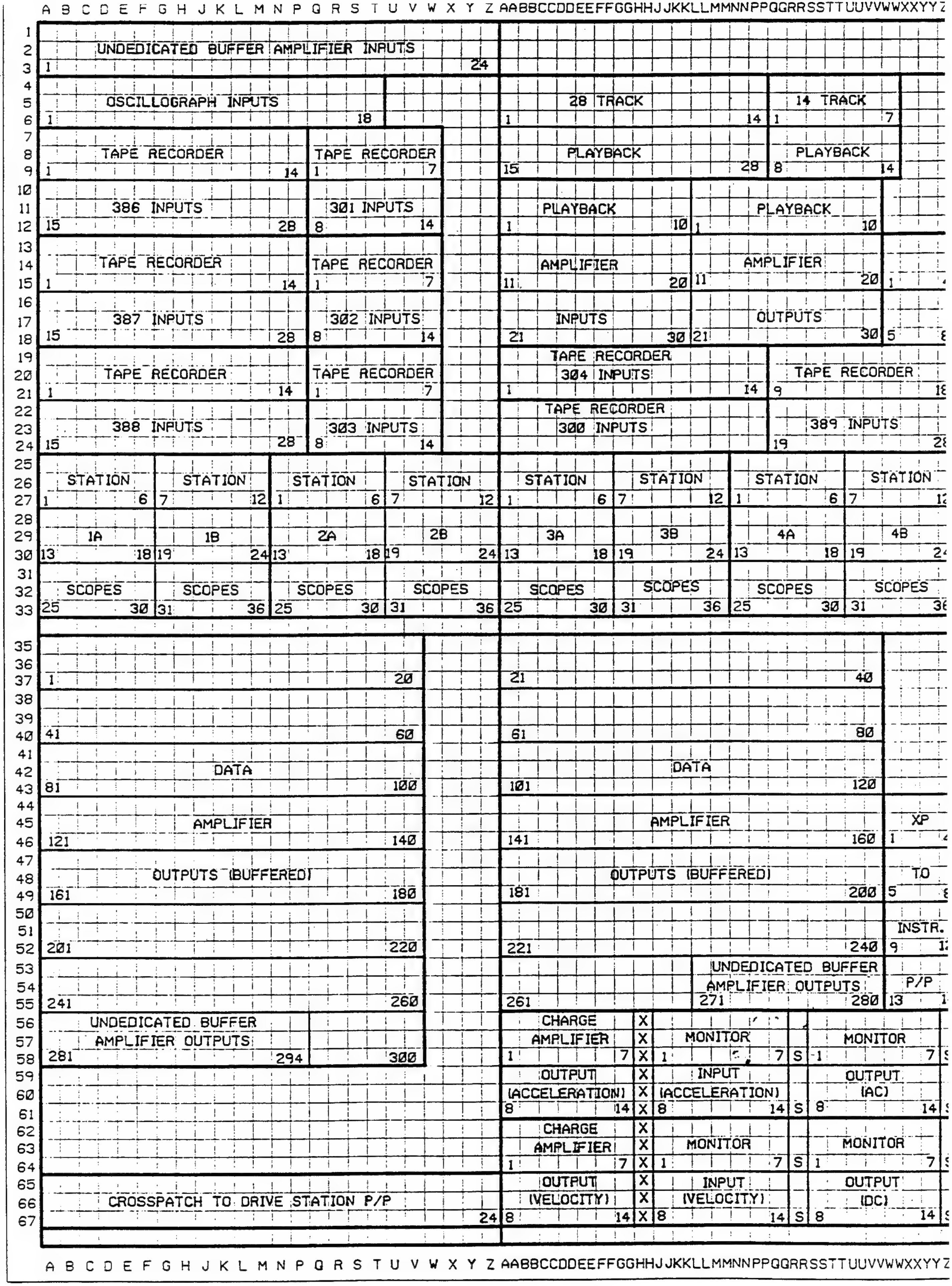


Figure 3.4. Aeromechanics Patch Panel Layout.

* If two or more gages per blade are displayed, put them on adjacent scopes.
* If more than one stage is displayed, have them progress through the scope channels in order by stage.
* If more than one bank of scopes is used, put all gages for each stage in the same bank.
* If both rotor and stator gages are displayed, and more than one bank of scopes is to be used, it may be advisable to put all the stators in one bank and rotors in another.

b. Scope Calibration -- Scope calibration for full-scale amplitude should reflect the accuracy with which stress signals must be analyzed during the test. In most applications, it is possible to set full-scale calibration at 30 ksida. This is desirable because the CRF scopes have +/- 3 vertical divisions. This should provide sufficient accuracy for detailed waveform interpretation. The tape recorders are normally calibrated for 80 ksida with the ability of being overdriven by 50%. So, for a high stress event that may saturate the scopes, the stress levels can be obtained from tape playback.

Occasionally stress response levels and/or scope limits are so low that the scopes will need to be calibrated for 15 ksida full-scale amplitude to observe waveforms adequately for aerodynamic implications.

c. Scope Triggers -- Each scope can be either internally or externally triggered. All scopes in the A/M station and in the SGMS are triggered on a 1/rev pulse from the drive station. The 1/rev trigger makes the signals appear stationary on the screen (only amplitude variation -- no motion in the horizontal direction) as long as they are comprised of integral order responses, such as resonant vibration. This assists the A/M monitor in visually monitoring his scopes. If a signal begins to move horizontally, he knows that some non-integral vibration is now present in that blade. This is crucial when throttling the test article as this may indicate the onset of flutter.

3.3.4 Tape Recording Details

The CRF has an impressive on-line analog recording capacity. There are four 28-channel tape recorders located at the A/M station and five 14-channel recorders across the control room by the Test Director. These nine recorders can be remotely controlled (start/stop) at the A/M station from a control panel located under the X-terminal. Each recorder is set up to record an IRIGA time code (Everything in the CRF -- computers, tapes, notes, SGMS -- is keyed to the same time code.) and a speed signal (usually a 6/rev but can be the 1/rev). The tape recorders which have the important instrumentation, e.g., the rotor gages, should also have a voice track provided to help find particular events during playback. This leaves about 160 channels for recording signals from strain gages, high response pressure

transducers, accelerometers, proximity probes, light probes, etc. When this was not enough recording capability for a particular test, additional portable tape recorders have been used.

a. Tape Speed -- Tape speed must be sufficient to provide unattenuated recorded signals up to the maximum frequency expected in the test program. Frequency limitations of the tape recorders allows faithful recording up to 5 kHz with 7 1/2 ips tape speed, 10 kHz with 15 ips, 20 kHz with 30 ips, 40 kHz with 60 ips , and 80 kHz with 120 ips. Instrumentation personnel will need to be informed of tape speed requirements in advance of the program.

b. Calibration -- As mentioned earlier the CRF tape recorders are calibrated for 80 ksida with the capability of being overdriven by 50%.

c. Continuous Recording -- When possible, continuous recording during the program is recommended, particularly during transients. If at an already determined "safe" steady-state operating condition, the tape speeds may be slowed so that only the fundamental vibratory modes are recorded. (This is because it is easier to degauss a tape with no significant data than it is to recreate stresses - if the tapes were off - during an inadvertent failure event.) Any tape changes should be made at these safe operating conditions. If the current operating condition is near a known problem area, or is on the edge of an unexplored region, the operating condition should be moved slightly into safe conditions during the tape change. The test director should be notified that tape changes are being made so that no changes in operating conditions will be made until the tapes have been changed and are again running. It is convenient, if possible, to use a "slave" tape for recording during steady-state operation, the regular tape being reserved for all transients (speed, stator schedule, throttles, etc.). The slave tape can be erased following the run if nothing significant happens during steady-state periods.

3.3.5 On-Line Data Analysis

Spectrum Analyzer. The spectrum analyzer is used on-line to determine the main component frequencies present is a selected signal. It can also be used to find out if a sensor is bad or breaking up.

Hard copies from each spectrum analyzer (there is one per monitoring station) can be printed using the hard copy printer in the A/M station. Typically each station's plot will be labeled with the station number, and the monitor should add any other pertinent information ASAP before he forgets what was happening when he made the print.

SGMS. On-line processed data (e.g., spectrums, autospectrums, waterfall plots) for one or four channels can be printed using the SGMS hard copy printer.

Oscillograph. These printouts can be useful on-line. They will have specific stress or vibration signal signatures. These can be helpful for a high stress event when the number of exceedances are needed to calculate the HCF life expended.

3.3.6 The Strain Gage Monitoring System

The Strain Gage Monitoring System (SGMS) processes, in real time, turboblading stress information. The SGMS is an integral part of the CRF A/M station, where 108 sensors can be monitored during testing. Possible sensors include dynamic strain gages, static strain gages, accelerometers, high-response pressure transducers, and thermocouples. The system relays to the A/M monitor the instantaneous status of the turboblading stress so that appropriate action can be taken to avoid potentially damaging vibratory stresses. The SGMS provides graphical analysis and alarm panel LED readouts. The SGMS will automatically inform the A/M monitor of an existing warning or alarm by lighting an LED and enabling an audible alert signal.

Functionality of the SGMS is twofold. Two distinct sections serve to monitor failure or display information. The failure analysis section of the SGMS is contained in the Two Channel Alarm Sensing Module (TCASM) units, while data display is performed in the Data Reduction Unit (DRU). Both units monitor information in both the time and frequency domain. The DRU will plot data only in the frequency domain but will provide tabular file information from the time domain.

3.4 BACKGROUND INFORMATION

It is helpful to have a variety of background information available to the aeromechanical engineers during the test program.

3.4.1 Design Data

As indicated in Figure 1.1, this data should be furnished by the engine contractor as early as possible before the test. Required data are:

* Analysis and bench test vibratory data, including Campbell diagrams and mode shapes for all stages,
* Scope limit definition for all monitored instrumentation, and
* Instrumentation definition, including location on the test article, calibration data, and recording requirements.

3.4.2 Test Plan

A copy of the test request and the detailed test plan for the subject investigation should be on hand for reference purposes. The goals of the test program should be understood. The planned testing schedule should be obtained for monitoring personnel scheduling.

3.4.3 Forms

The job of logging information during testing and summarizing pertinent test and instrumentation items can be greatly simplified by using previously prepared forms. Some handy ones recently used in the CRF are described below.

a. Aeromechanics Station Checklist, Figure 3.5 -- a list of things to be done, before and after each test run, to ensure that the A/M station is fully operational.

b. Aeromechanics Station Oscilloscope Layout, Figure 3.6 -- this is used to plan the instrumentation distribution through the four A/M monitoring station's scopes to make sure that the best monitoring can be accomplished. This also documents the final layout of the A/M station scopes.

c. Aeromechanics Run Summary, Figure 3.7 -- completed at the end of each run. It's a condensed version of the daily on-line log sheets from each monitoring station. Some run statistics are also noted here.

d. Analog Tape Recording Log, Figure 3.8 -- this log is kept during the test program. This is used to document the tape numbers, tape stops and starts, tape changes, and tape change time on each of the analog tape decks used to record aeromechanical data during each run. This information is invaluable for post-test data reduction.

e. Aeromechanics Instrumentation Status Summary, Figure 3.9 -- used to indicate the health status of the instrumentation for each A/M monitoring station.

f. Daily On-Line Log Sheet, Figure 3.10 -- accurately keeping these logs is the heart and soul of A/M monitoring. These logs provide a record of test conditions and events and the time they occurred, as well as noteworthy instrumentation events for each A/M monitoring station. To facilitate post-test run summary compilation, these logs are a standard form for each monitoring station.

Notes are taken during the test beginning with the start motor sequence and ending with whatever shutdown procedure occurs. Notable events include, but are not limited to: stalls, resonance, flutter, surge, bypass valve movement and position, variable geometry movement, sensor failure or breaking up, tape changes, and test rig stops. All events

Figure 3.5. Aeromechanics Station Checklist.

Test Program: ________________________

Run No.:_____

Run Date (Julian):________ (   )

PRE-TEST

___Oscilloscope Racks Turned On

___Hard Copy Printer Turned On (30 min warmup req'd)

___SGMS System On-line and Ready (15 min warmup req'd prior to executing "SGMS")

- Color Monitor
- Versatec
- Printer
- SD380Z

___On-line C/D System Enabled and Setup

___CRF Tape Recorders Turned On W/Tapes Mounted

___Tape Log Sheets at each Tape Recorder

___Tape Numbers Recorded in On-line Log Sheets and Tape Logs

___Monitoring Patch Panel in Place

___Time Code Readers Setup

- At Tape Recorder
- At SGMS

___Spectrum Analyzers Setup (ID's, EU's, Etc.)

___Variable Gain Oscilloscope Check (Strain Gages, Accelerometers)

___Sine Wave Calibration Check W/Results Recorded in Log Sheets

___Sine Wave Calibration Recorded On Tape

___Tape Dubbing Cables Removed, Tape Recorders Returned to Proper Recording Configuration

___ATDS Cables Removed, Tape Recorders Returned to Proper Recording Configuration

___Station Notebooks Out and Test Plan W/Ammendments Reviewed

___Daily Run Summary Started

___No Critical Trouble Logs for this Station

___Overhead Lights Adjusted

The Aeromechanics station is correctly configured for this run. Discrepancies are noted in the Aeromechanics Run Summary and Daily Run Notes.

Signed/Time:________________

POST-TEST

___Sine Wave Calibration Check Performed and Results Recorded in Run Notes (May be omitted in certain circumstances - annotated in daily notes)

___Sine Wave Recorded on Tape Decks (May be omitted as in above)

___Power turned off to equipment

___SGMS Offline, "Shutdown" Executed, Power Off - Printout Data Logging Files As Necessary Prior To Shutdown

___Tape Removed From Tape Heads

___Instrumentation Status Summary Completed

___Daily Run Summary Completed (May be deferred to next day prior to run)

___Trouble Logs Submitted (Yes/No) - File Copy if Yes

Figure 3.6. Aeromechanics Station Oscilloscope Layout.

Test Program:____________________________ Date:______________

STATION NO. 1

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

STATION NO. 2

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

STATION NO. 3

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

STATION NO. 4

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

Figure 3.7. Aeromechanics Run Summary.

Test Program:____________________

Run No: ________

Run Date (Julian): __________ (   )

Monitor (s): ______________________________

____

Configuration:______________________________

____

Test Objectives:______________________________

____

Items Noted Prior to Test:____________________

____

____

____

Run Statistics

Total Time this Run: _____ Hrs _____ Min

Total Run Time to Date: ______ Hrs ____Min

Max Mech Speed this Run __________ RPM

Max Mech Speed to Date ___________ RPM

Total Stalls this Run: ____________

Total Stalls to Date: _____________

Total Time At or Above

100% Speed this Run: _____ Hrs _____ Min

Total Time At or Above

100% Speed to Date: _____ Hrs _____ Min

Run Chronology / Significant Aeromechanics Events:

Figure 3.7. Aeromechanics Run Summary (Concluded). Page 2

Run Chronology / Significant Aeromechanics Events (Contd.)____________________

Suggested data reduction:

Preliminary Conclusions / Recommendations:

Trouble logs submitted ? (yes/no) _______(File copy if yes)

Signed:____________________________

Reviewed:____________________________

Figure 3.8. Analog Tape Recording Log.

Page:__________

386 ips	387 ips	388 ips	389 ips	300 ips	301 ips	302 ips	303 ips	304 ips

Figure 3.9. Aeromechanics Instrumentation Status Summary.

Test Program:________________________ At Conclusion of Run No:____

STATION NO.

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

STATION NO.

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36

KEY TO SYMBOLS:

/	Channel is good
bu/gd	Channel is breaking up/grounded - intermittent signal
+n	Signal plus some noise
+N	Signal plus heavy noise
N!	Signal masked/contaminated with noise
?	Data integrity is uncertain
X	Channel is bad or has been pulled

Station:______ Test Program:________________________ Run No:______ Date:____________ Page:____/_____

Monitor:______________________

Configuration:					A												
New Tapes:			Continuing Tapes:		B												
					C												
Time	RPM	%Nc	DV	Test Comments													

***** SENSITIVE INFORMATION --- REQUESTS FOR THIS INFORMATION SHALL BE DIRECTED TO WL/POTX *****

Figure 3.10. Daily On-line Log Sheet.

recorded should have their description, time of day, mechanical speed, percent corrected speed, and any other significant test conditions. Scope limits (in volts, mils, ksida, etc.) are also noted in the logs. Overall signal levels can be estimated from the scopes, and by using the spectrum analyzer, each signal can be broken down into its component frequencies and magnitudes.

Care should be taken not to write classified information on these logs since they are intended to be unclassified.

g. Magnetic Tape Log, Figure 3.11 -- these are kept with each analog tape used during the test. This is useful in post-test data reduction since it tells what the last tape number was and what the calibration data tape number was.

h. Analog Tape Recorder Configuration, Figure 3.12 -- this form shows the initial analog tape recorder configuration with each sensor location on the tape. This gives a concise overview of the entire tape recordings.

i. Analog Tape Recorder Configuration History, Figure 3.13 -- shows the original configuration of the tape recorder at the start of the test and the dated changes which were made during the course of the test.

3.5 POST-TEST DATA REDUCTION AND ANALYSIS

3.5.1 The Strain Gage Monitoring System

Real-time analysis is not the sole function of the SGMS. The system was also designed to post-process data through the use of analog tape recorders. The change from real-time to post-processing is designed to be transparent to the system. Once processing begins, the user selects from a hierarchical menu system to boot, configure, edit, or analyze the sensor or channel of interest. Through use of the menu, alarm and warning specifications may be set, sensor parameters may be accessed, speed and frequency ranges may be established, spectrum analysis operation may be configured, sensor maintenance may be performed, and data logging and tape control may occur.

3.5.2 The Analog Tape Digitizing System

This system is located behind the A/M station as shown in Figures 3.1 and 3.2. With the analog tape digitizing system (ATDS) we can perform reduction and analysis of analog data, as well as generate digital data files and standard format tapes. Available tools include FFT's, Finite-Impulse-Response (FIR) filtering, mathematical operations, statistical analyses, peak hold, frequency tracking, and cross-reference FFT's. These allow cascade plots,

Figure 3.11. Magnetic Tape Log.

REEL_______________ RECORDER___________ TAPE SPEED__________ ips
DATE_______________ CENTER FREQ.________kHz
TEST PROGRAM______________________ SPEED TIME BASE__________

Trk	Parameter	Cal Value		Trk	Parameter	Cal Value	
1				15			
2		mvpp =		16		mvpp =	
3		mvpp =		17		mvpp =	
4		mvpp =		18		mvpp =	
5		mvpp =		19		mvpp =	
6		mvpp =		20		mvpp =	
7		mvpp =		21		mvpp =	
8		mvpp =		22		mvpp =	
9		mvpp =		23		mvpp =	
10		mvpp =		24		mvpp =	
11		mvpp =		25		mvpp =	
12		mvpp =		26		mvpp =	
13		mvpp =		27		mvpp =	
14		mvpp =		28		mvpp =	

Rdg	Time	RPM	Test condition and/or parameter information

Cal Reel____________ Last Reel______________ Next Reel_______________
Comments____

Figure 3.12. Analog Tape Recorder Configurations.

Test Program:____________________

Tape Speed				
.....Deck / Channel....	386	387	388	389
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15	Time Code	Time Code	Time Code	Time Code
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				

Figure 3.12. Analog Tape Recorder Configurations (Concluded).

Test Program:_______________________

Tape Speed					
....Deck / Channel.....	300	301	302	303	304
1					
2					
3					
4					
5					
6					
7	Time Code	Time Code	Time Code	Time Code	Time Code
8					
9					
10					
11					
12					
13					
14					
Edge					

Figure 3.13. Analog Tape Recorder Configuration History.

TEST PROGRAM: **RECORDER NO:** **RECORDER SETUP: WB GRP 1**

CHANNEL NO.	ORIGINAL AS OF: HEADER/GAIN	CHANGE 1 HEADER/GAIN	CHANGE 2 HEADER/GAIN	CHANGE 3 HEADER/GAIN	CHANGE 4 HEADER/GAIN
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15	TIME CODE				
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					

Figure 3.13. Analog Tape Recorder Configuration History (Concluded).

TEST PROGRAM: **RECORDER NO:** **RECORDER SETUP: WB GRP 1**

CHANNEL NO.	ORIGINAL AS OF: HEADER/GAIN	CHANGE 1 HEADER/GAIN	CHANGE 2 HEADER/GAIN	CHANGE 3 HEADER/GAIN	CHANGE 4 HEADER/GAIN
1					
2					
3					
4					
5					
6					
7	TIME CODE				
8					
9					
10					
11					
12					
13					
14					

Campbell diagrams, waterfall plots, frequency spectrums, and time histories to be generated. The ATDS is shown in Figure 3.14.

3.6 TEST PHASES AND OBJECTIVES

The phases and objectives of each test program are somewhat different. However some are common to most programs. These are described below.

Mechanical Checkout

1. Ensure aerodynamic and A/M integrity of the test article up to 105% Nc.
2. Define the aerodynamic performance to include peak efficiency and nominal operating line (NOL) conditions using a predetermined vane schedule.
3. Evaluate the effect of the bypass valve (BPV) and determine the core discharge valve (CDV) and BPV settings for the proper bypass ratio (BPR) on the NOL.
4. Define the reduced inlet conditions to operate at the design speed.
5. Determine the settling time of the test article configuration.
6. Verify the facility response to the surge recovery command.

Vane Optimization for Efficiency

1. Define vane schedules for maximum efficiency between high speed and 70% Nc.
2. Define the influence of variable vane angles on airfoil stress levels.

Performance Mapping with Optimized Vane Schedule

1. Determine the optimum performance to the stall line of the test article between 50% and 105% Nc.
2. Determine the airfoil vibratory stress levels over the compressor operating range from idle to 105% Nc.

Off-Schedule Performance Mapping

1. Define part-speed performance with one or more stages unloaded.
2. Determine the airfoil vibratory stress levels with one or more stages off-schedule.

Aerodynamic Performance with Inlet Distortion

1. Determine the performance variation and stall margin degradation resulting from inlet flow distortion.
2. Quantify the induced flow distortion.

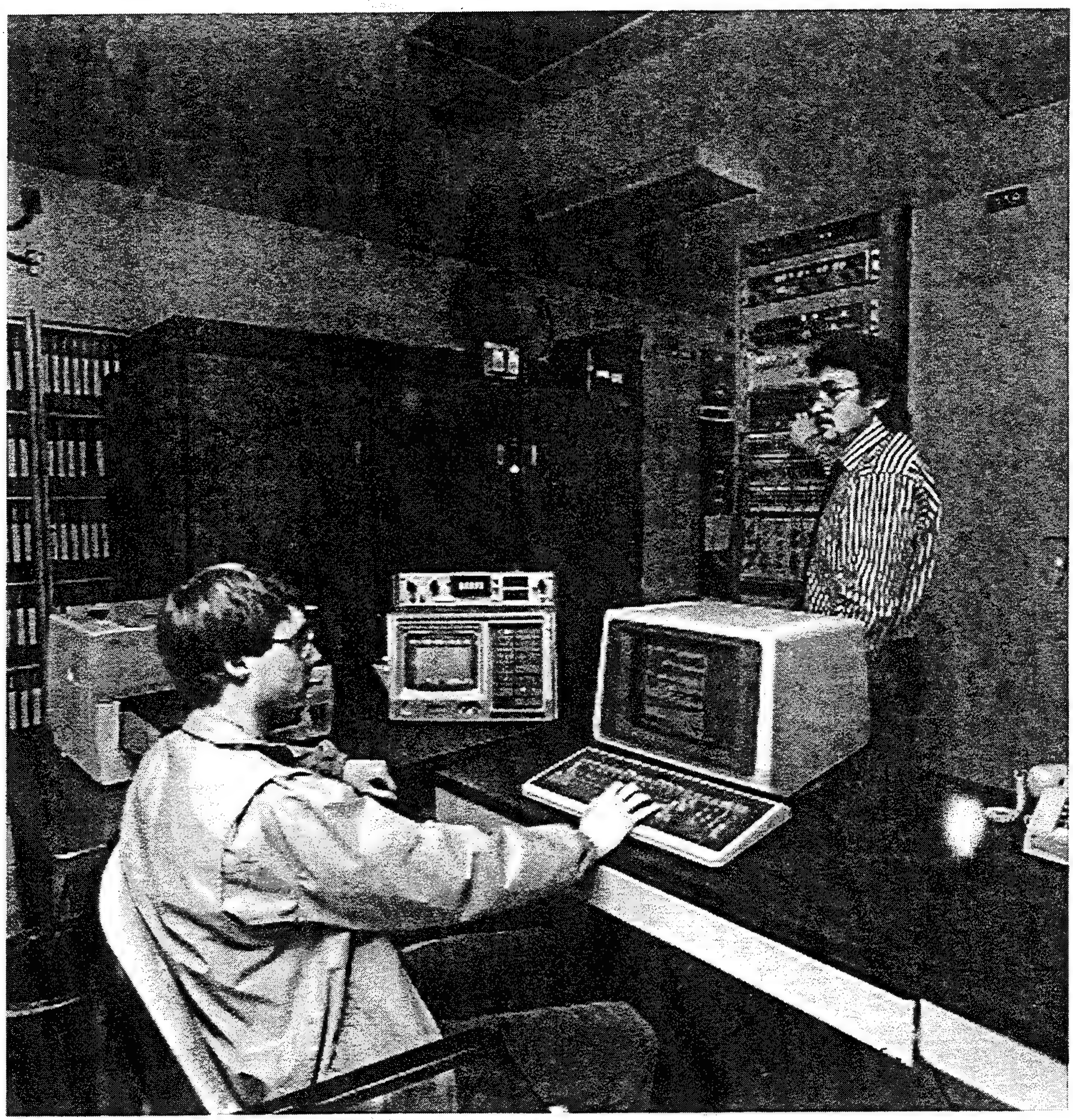


Figure 3.14. Analog Tape Digitizing System.

3. Determine the influence of inlet pressure distortion on the airfoil vibratory stress levels over the compressor operating range from 70% to 105% Nc.
4. Determine the influence of inlet rakes and other instrumentation on the measured performance from 50% to 105% Nc.

3.7 EMERGENCY CONDITIONS

These are defined to return the test article to a safe condition from a potentially damaging condition. There are three kinds typically encountered:

1. Stall Recovery: may be manual or automatic, depending on the urgency. Most are automatic. In extracting from this condition, the IGV's and stators are returned to their nominal schedule and the DV is opened to the LOL.

2. Flutter Recovery: similar to the above. However, if the flutter condition persists after opening the DV and unthrottling to the LOL, a decel to the minimum speed and/or a shutdown will be executed.

3. Emergency Speed Reduction and/or Shutdown: results in a decel at predetermined rates to minimum or zero speed.

For many reasons, the A/M monitor may need to interrupt the progress of the testing. It is important that consistent commands are used so that no confusion exists with the test operator. To that end, the following operational commands and procedures are suggested.

1. **Hold** -- Maintain all parameters at the levels when the hold command was called.

2. **Backoff** -- Return all parameters to the levels previous to the change.

3. **Min/Idle Speed** -- Reduce speed at a decel rate of (usually) 100 rpm/sec to minimum/idle speed. The A/M monitor will open the DV.

4. **E-Stop** -- This calls for an emergency shutdown at the maximum decel rate to zero speed. There are three stop commands, E-Stop 1, 2, and 3, corresponding to decel rates of (usually) 500, 750, and 1000 rpm/sec. In an A/M emergency, we want the test article stopped as soon as possible, so an E-Stop command from an A/M monitor will be taken as an E-Stop 3.

5. **Decel** -- Reduce speed until the A/M monitor judges the condition to be clear.

6. **Accel** -- Increase speed until the A/M monitor judges the condition to be clear.

4.0 REPRESENTATIVE STRAIN GAGE SIGNALS

After sampling S/G signals from the inventory of magnetic tape records for accurate categorization, it was found that there was virtually no difference between rotating and stator S/G signals. A similar argument holds for signals from integral, cantilevered, part-span shrouded, and tip shrouded blading. Thus these variables do not have to be considered when discussing different S/G signals.

Experience has shown that the frequency spectrum of a S/G signal is an almost indispensable means for identifying vibration types. Sometimes however, the type of vibration cannot be identified without observing the signal before the actual event (e.g., the occurrence of a misrigged vane) where a Campbell diagram would be more useful. Thus, to get enough time samples for a vibratory analysis, it becomes apparent that "on-line" monitoring is a relative expression which really means anything from a fraction of a second to several minutes. For example, where frequency spectra can be obtained in milliseconds, Campbell diagrams require minutes since they are from data acquired within a speed range, say, from idle to design speed.

This chapter discusses the most significant types of vibration according to their S/G signals. This will include typical S/G signals, in real time as amplitude-time plots, frequency spectrums, and/or Campbell diagrams. Also included are conditions that can produce the different vibrations.

4.1 TYPES OF VIBRATION SIGNALS

The types of vibration are classified in the following categories:

Forced Vibration

- Nonresonant vibration
- Resonant vibration
- Rotor blade tip rub
- Unlatched or misrigged vane
- Separated flow vibration (SFV)
- Rotating stall
- Pulse-type stall and surge

Self-Excited Vibration

- Stall flutter
- Supersonic shock flutter
- Choke flutter

Malfunctioning or noisy instrumentation should also be included:

Invalid Signals

Slip ring noise

Broken (open) or grounded S/G or lead

4.2 FORCED VIBRATION

The structural periodicity of a compressor naturally results in periodic forces and consequently in aeromechanical vibrations. The source of most periodic forces is a circumferential disturbance in the flowfield. Some possibilities are: inlet distortion, rotor blade and stator vane wakes, stationary rakes, misrigged or missing vanes, damaged blades, and interstage bleed extraction. Excitation wakes from the introduction of traverse probes during testing also belong here. In a multistage compressor, rotor/stator interaction complicates an already complex loading condition. Because of the rotation and structural periodicity of rotor blades and stator vanes, the frequencies of these excitations are integer multiples of rotor speed, i.e., engine orders (EO's).

Many types of vibratory forced response can happen depending on the forcing function, the stage in question, and the operating regime of the compressor.

4.2.1 Nonresonant Response

This type of vibration occurs when the airfoil responds to an excitation whose frequency does not correspond to the airfoil's natural frequencies. This can be seen in Figure 4.1 where the forced nonresonant response is 1/rev, with the first blade mode being higher. The stimulus occurs at an integer multiple of rotor speed since it is created when the blading passes through a flow distortion. In this case it can be seen that as the rotor speed increases, the nonresonant response grows monotonically and follows the 1/rev line.

4.2.2 Resonant Vibration

Resonant response happens when the excitation frequency corresponds to one of the airfoil's natural frequencies. The Campbell diagram in Figure 4.1 shows that when the small nonresonant 3/rev vibration coincides with the 2F mode frequency a resonant response occurs at about 12,000 rpm.

Since resonant responses occur when an airfoil natural frequency is an integer multiple of rotor speed, expected possible resonances can be determined before the compressor test using the predicted Campbell diagram. Every intersection of a blade frequency with an EO, or per rev line, is a possible resonance. Fortunately only a few of these materialize, and are usually within tolerable limits. Since compressor blading have many natural frequencies, several resonances can happen at any one rotor speed. When the excitation is from wakes

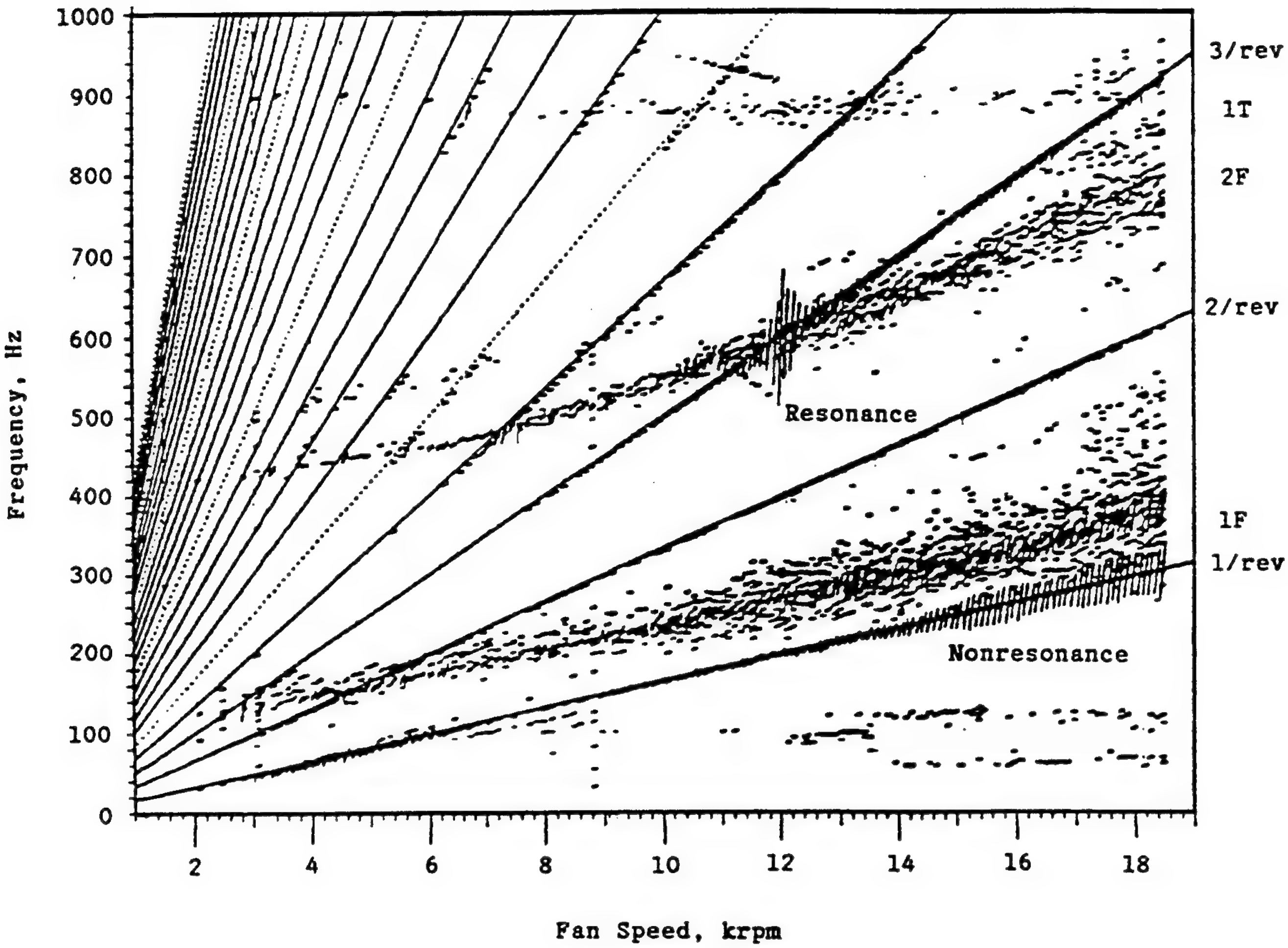


Figure 4.1. Resonant and Nonresonant Response.

shed from adjacent stages, the excitation frequencies are equal to the rotor speed multiplied by the number of airfoils in that stage (can be an integer multiple) and are called blade-passing frequencies. This type of vibration may be encountered by either rotors or stators. Not only can we have blade passing excitations but stage differences between forward and aft rotor passing frequencies. Also, in a subsonic environment, the potential effects from aft stages may effect the rotor's vibration.

Resonant vibratory signals are best illustrated in a Campbell diagram whose history covers the time prior to, during, and after the resonant speed. The history before the resonance shows a rapid increase in the stress amplitude as the excitation frequency approaches the blade natural frequency. The history after resonance is perhaps the most important because it shows the rapid decrease of the stress amplitude as the excitation frequency passes the blade natural frequency, and without it we cannot tell if the signal blossoming character is resonance or flutter. (As will be discussed later, flutter usually occurs at non-integer multiples of rotor speed -- but nothing in the physics of the problem says that flutter cannot happen at an EO, in which case the signal amplitude would not decrease as the excitation frequency passes the blade natural frequency.)

4.2.3 Rotor Blade Tip Rub

This excitation is entirely mechanical in nature and almost always involves the rubbing contact of a rotor blade tip with the casing. Normally, the radial clearance between blade tips and casing is kept small for enhanced aero performance. Thus rapid acceleration of a relatively cool compressor could permit the rotor to grow faster under centrifugal loading than the casing expanding with increasing temperature. Large amplitude blade vibration as well as rotor unbalance response can result from a tip rub. Nonconcentricity of the rotor and casing or a slight local bulge in the casing may also cause a blade tip rub. More that one hit per revolution happens when there is more than one bulge in the casing. Engine or casing vibration characterized by large relative blade-to-casing radial motion could also induce rubs. Axial interference, rare but not impossible, occurs if blading becomes permanently bent, by foreign object ingestion, stall, surge, or some other means, to the point that axial contact is possible. Stall-induced blade vibration, in combination with transient loading during surge, has been known to reach magnitudes which result in contact with an adjacent blade row.

A strain gage on a rubbed blade has a distinctive time signature of an initial spike, due to the sudden impact, followed by damped vibration decay at one (usually) of the blade's natural frequencies, typically 1F, until the rub occurs again and the cycle is repeated. (This signature has also been described as looking like a Christmas tree.) The rate of decay is a function of the blade's damping characteristics. Figure 4.2a shows a S/G response at the onset of a single rub. The waveform in Figure 4.2b shows two fully developed rubs separated be about 154 degrees. Unlike the misrigged vane excitation described below, a tip rub does not usually persist since rubbing erodes either the casing and/or the blade tip, i.e., the rub is self-limiting.

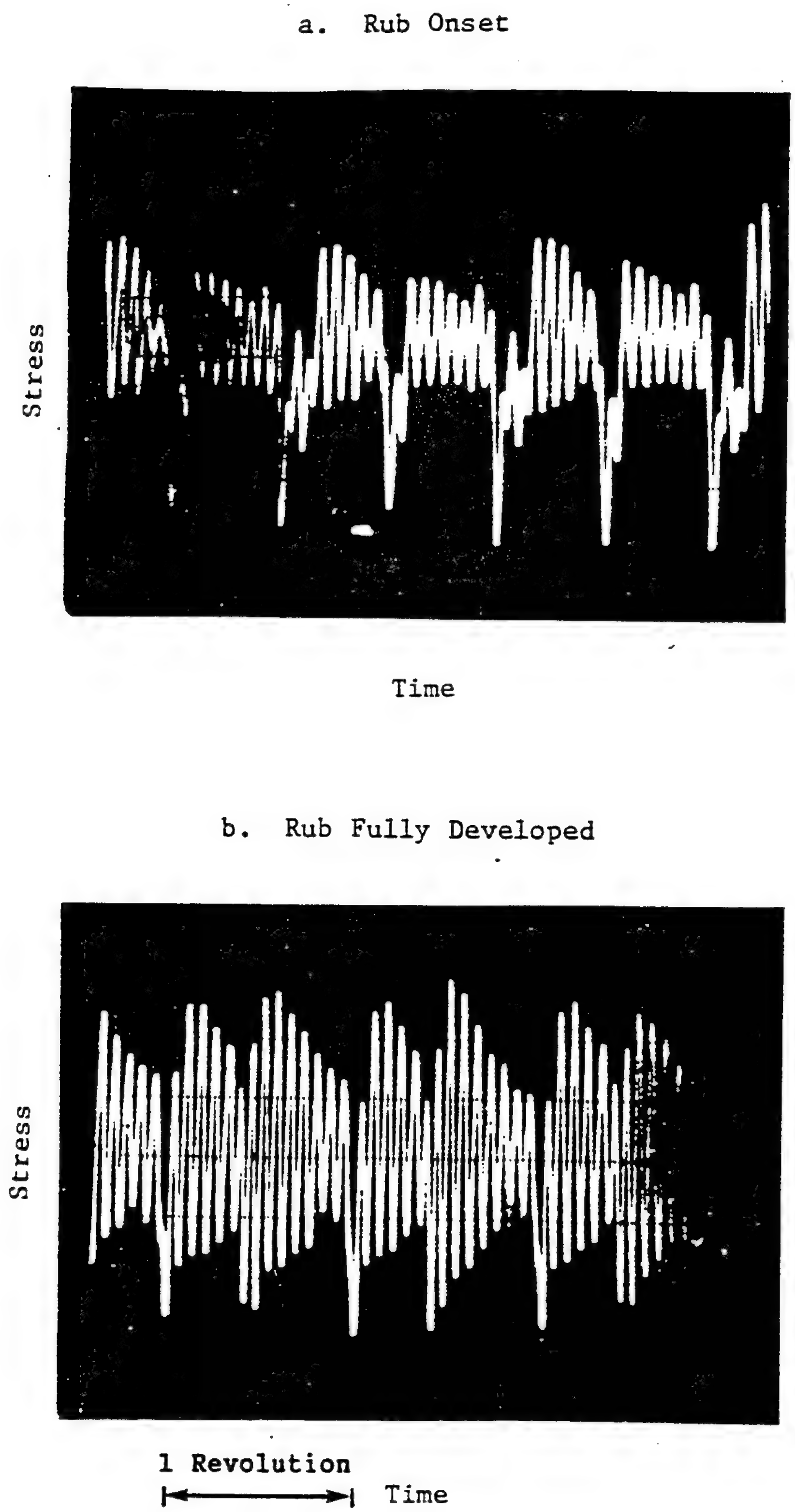


Figure 4.2. Strain Gage Time History During Blade Tip Rub.

4.2.4 Unlatched or Misrigged Vane

The S/G signal of a rotor blade behind an unlatched vane is like a rub but with a more rounded peak. The dominant excitation frequency is 1/rev accompanied by an integral order response at a blade natural frequency. The misrigged vane(s) will shed wakes much stronger than the other vanes in the stage so that it will be seen as a generator of a 1/rev stimulus and its harmonics by all the rotor blades. As the vane setting is increased, the wake shed by the misrigged vane becomes stronger and will contain many harmonic components. This can be seen in the amplitude/speed charts in Figure 4.3. The high frequencies arise from the Fourier components of the spatially narrow circumferential aerodynamic distortion exciting the blade's higher modes. In the instance when more than one vane is unlatched, identification is more difficult. A Campbell diagram of the stresses in a rotor blade behind a misrigged vane in the midstage of a compressor is shown in Figure 4.4.

A vane may be misrigged by assembly error, bent vane lever arms from a hard stall, fatigue failure of lever arms, loose vane attachment, and broken vane trunnion. FOD from ingested debris could also result in incorrect vane settings.

Most of the rotor blade response in a stage adjacent to misrigged vanes would be a forced vibration at frequencies of EO's with a resonant blossoming at the natural frequency/EO crossings. The most reliable way to identify the presence of misrigged vane excitation is to look at S/G signals from the other instrumented blades in the stage. They all will be showing the above signal characteristics.

4.2.5 Separated Flow Vibration

The term SFV is applied to the random response of blading in one or more of their natural vibration modes. This type of response is induced by turbulence, either that existing in the main airflow, or induced on the cascade (airfoil) itself due to a high stage loading (either positive or negative directions). Stimuli arise from partial flow separation on the airfoil due to large flow incidences. The blades act as a filter, responding to excitation in the frequency range immediately surrounding the natural frequency for each vibration mode. As a rule, response in the lower modes is predominant. The degree of turbulence is indicated by the magnitude of random modulation with time. Accordingly, terminology can be developed relative to percent modulation to describe the SFV. S/G signal time histories from three blades in SFV are shown in Figure 4.5.

Occasionally, a sudden increase in SFV can occur with the introduction of an interstage traverse or aerodynamic probe during testing. Another consequence of increasing SFV, such as caused by changing the compressor operating condition, is the possible impending stall and surge, or flutter. (Flutter S/G samples, presented later in Figures 4.8 and 4.9, show SFV before the instability occurs.) In multistage compressors, sometimes the

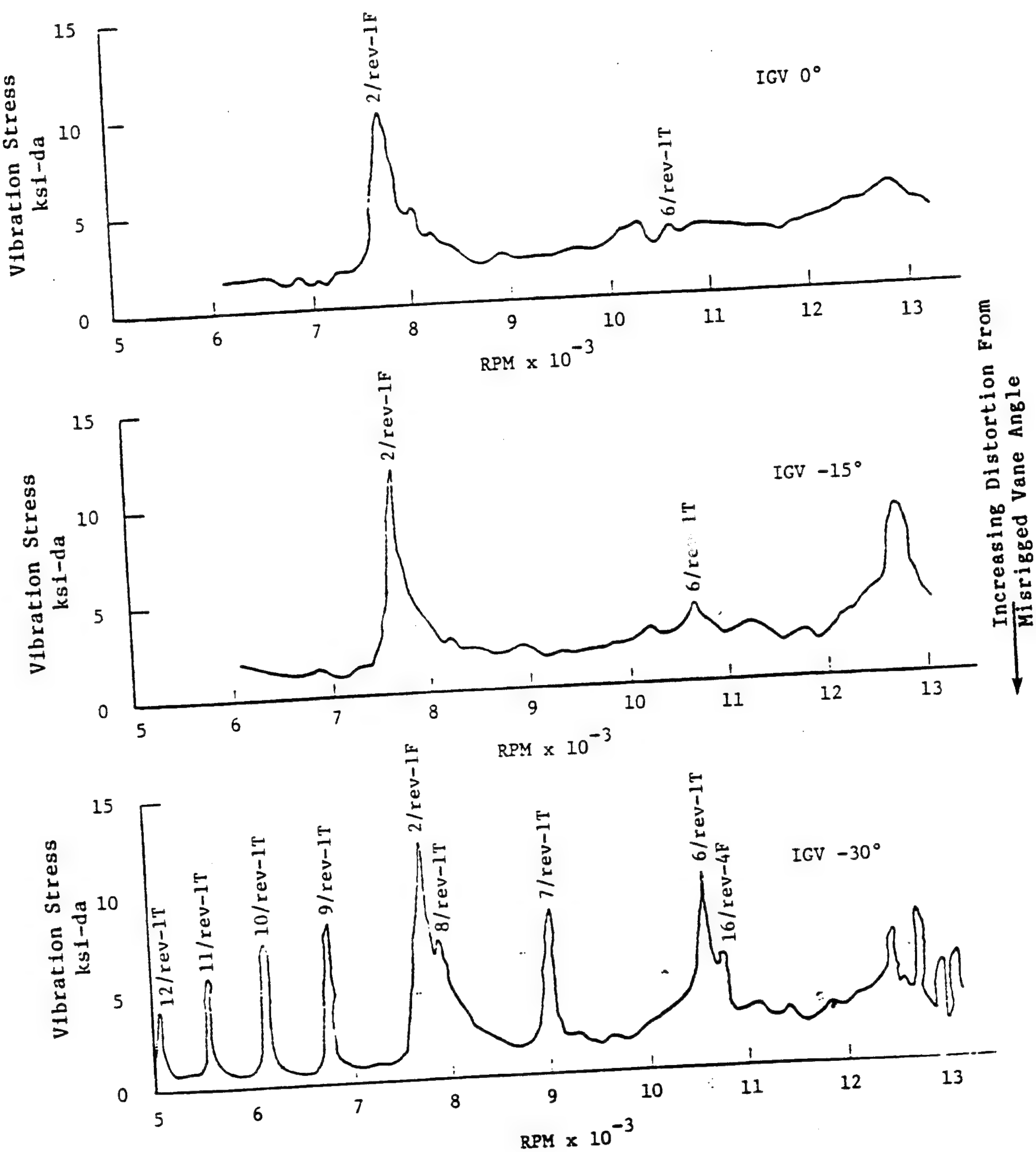


Figure 4.3. Effect of Single Off-Angle IGV on Rotor Blade Resonant Stress.

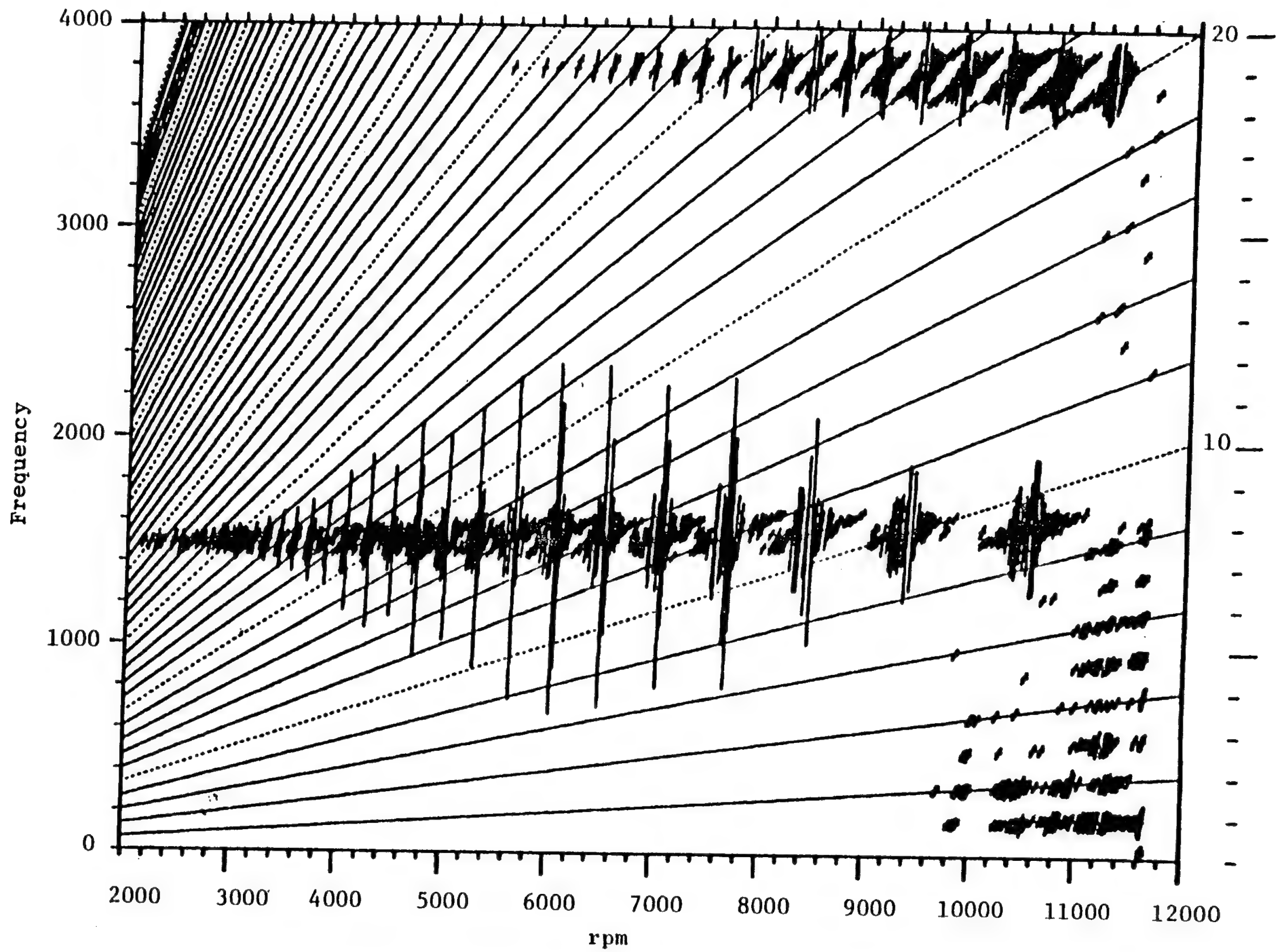


Figure 4.4. Blade Stress Response to Misrigged Vane.

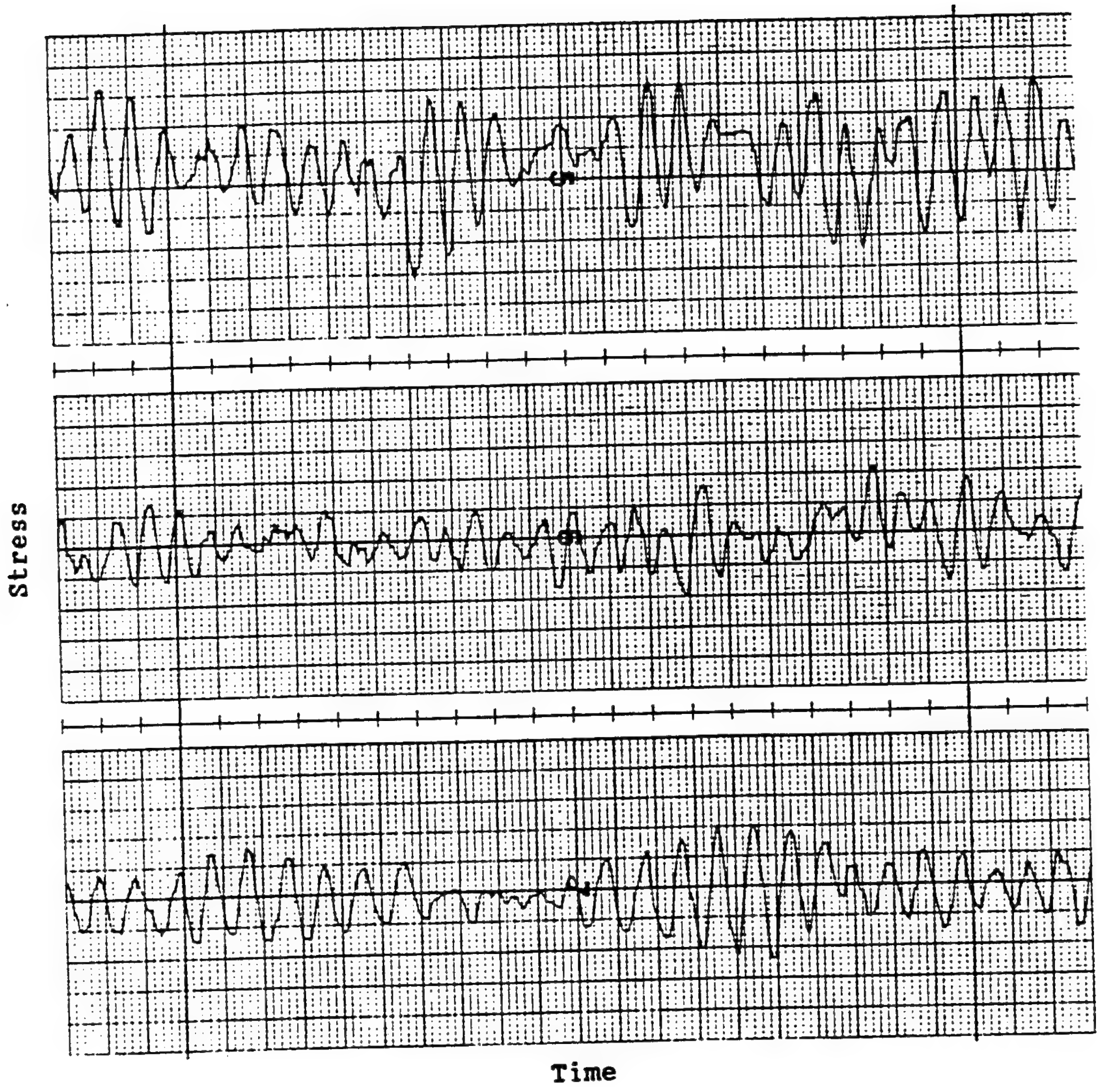


Figure 4.5. Samples of Strain Gage Signals During SFV.

front stages will encounter high levels of SFV at the low-to-mid speed range, and the aft stages will experience SFV at higher speeds. This is governed by the aerodynamic "stage matching" in the specific compressor.

4.2.6 Rotating Stall

This type of stall is characterized by the existence of one or more regions of low airflow in the annulus, with each region rotating in the direction of the rotor at about half the rotor speed (actually observed at values between 35 and 65% speed). These low flow regions are called "stall cells." The boundary between good and low flow regions is very sharp, with a sizable change in cascade loading being experienced by blades and vanes as the edges of the stall cell passes. Typical blade response characteristics are shown by the three waveform cases shown in Figure 4.6. During severe rotating stall conditions, blade vibration tends to be rather chaotic during the time the blade is immersed in the stall cell. Often this response does not have time to clear up completely between stall cell passing, thus making the stall cell transient. At times it is apt to look like a rub as in Figure 4.6b, but the apparent "hits" will occur at about 0.5/rev, rather than the 1/rev characteristic of rubs. For mild stalls, or heavily damped structures, the response may be limited to the transient load (pivoted stators, and shrouded blades tend to fall into this category).

"Full stalls," which represent the stall line shown on performance plots, occur as full annulus rotating stalls at all speeds for most fans, and for multi-stage compressors in the low-to-mid speed range. Marginally aerodynamically matched compressors can also encounter full rotating stalls in the high speed range, usually preceded by a stall pulse (see the next section). By "marginally aerodynamically matched," it is implied that the middle stages, whose loading does not change much with pressure ratio at high speeds, are too heavily loaded, and after sustaining full stall, remain stalled as the pressure ratio is lowered (this is hysteresis). This characteristic occasionally induces the stall to be locked in, thus requiring the rotational speed to be reduced to clear the stall. These full rotating stalls usually involve only one cell which extends pretty much all the way through the fan or compressor. The asymmetric loading on the rotor during stall is fairly large, and as a rule, induces strong test article vibration. This, in combination with excessive temperature due to the low through-flow, makes it necessary to clear a full rotating stall at high speeds as quickly as possible. In fact, the design intent of the compressor is usually to encounter surge rather than full rotating stall at the higher speeds.

The front and middle stages of a compressor usually experience the largest vibratory stresses during rotating stalls. But they are normally much less severe than those encountered in the pulse-type stalls or surges discussed below.

4.2.7 Pulse-Type Stall

This type of stall involves complete momentary breakdown of the compressor flow, the duration of which is controlled primarily by the volumetric characteristics of the portion of

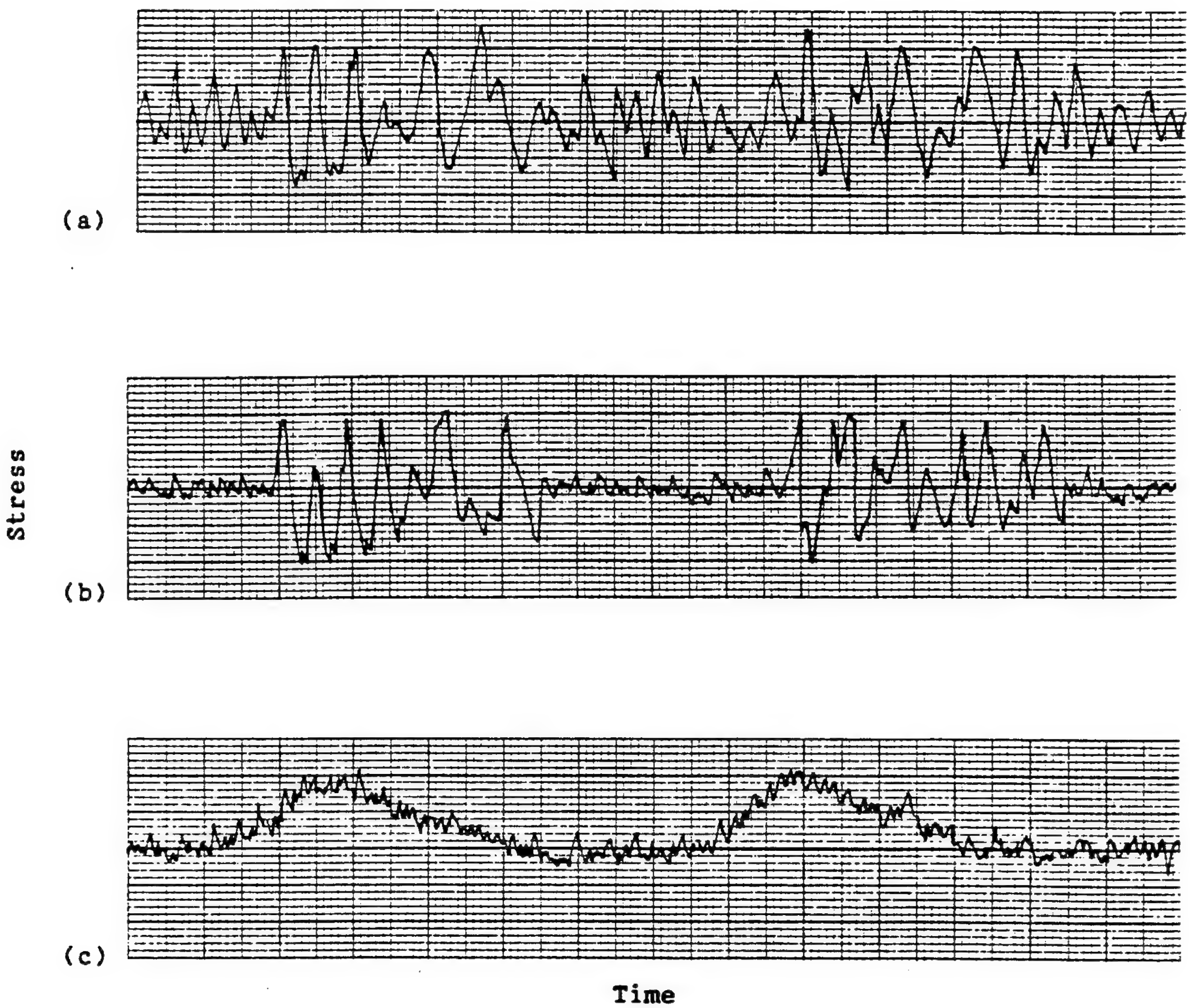


Figure 4.6. Blade Responses During Rotating Stall.

the total air induction system affecting the component (Helmholtz resonator effect). The airflow not only stops momentarily, but has frequently been observed to reverse direction during the pulse -- this is called surge. This action results in an audible sound similar to a shotgun discharge. Pulse durations have been observed to be as brief as 50 to 70 milliseconds for small compressors to an extreme of 1.5 seconds in a large compressor. This type of stall will have repeated pulses until some stall-clearing action is taken, like reducing the pressure ratio. The short duration pulses will repeat more frequently than those of long duration, and have been observed as rapidly a 11-12 pulses per second. To preclude a potential problem of HCF damage, such rapid stall pulse occurrences require particularly expeditious stall-clearing actions. Rotor blade vibration during pulse-type stalls builds up in amplitude very rapidly as the compressor flow breaks down and reduces to normal levels as the flow recovers as depicted in Figure 4.7. Combined aerodynamic and acoustic effects may cause the blade response to wildly fluctuate a few times during the pulse. Stator vane response, on the other hand, tends to be strongest during the periods of flow breakdown (early in the pulse) and flow re-establishment (late in the pulse).

Pulse-type stall is indicative of instigation by migrating stages, i.e., stages whose loading at a given speed increases appreciably with increasing compressor pressure ratio. Thus, the sudden pressure ratio decrease during the stall reduces the loading of these stages, tending to clear the stall. In the high speed range, these migrating stages are the rear ones, extending further forward into the middle block in the mid-speed range (75-80% speed). Pulse-type stalls rarely occur below 70-75% speed. As may be inferred from the above discussion, pulse-type stalls do not happen on single stage fans, and rarely on two-stage machines. Generally, four or more stages are needed before expecting pulse stalls in the high speed regime. Pulse stalls on two or three stage machines requires virtually identical loading for the stages to stall, thus more readily allowing complete flow breakdown to occur.

Pulse-type stalls produce much higher stress than do full rotating stalls. Also, maximum response is usually in the mid-stage sections, with the forward and aft stages rarely exceeding scope limits. Thus assessment of possible HCF damage accumulation due to these stall stresses, which can far exceed scope limits (sometimes as much as 200-300%), may be necessary during the test program.

These stall stress signals are characterized by modulated amplitude response of the 1F or 1T modes, or both. Preceding stall, the level of SFV usually increases, so this can be the indicator of imminent stall. Stall vibration is a forced response at the blade's natural frequencies which are independent of rotor speed.

4.3 SELF-EXCITED VIBRATION

Aeroelastic instability, or flutter, of turboblading is a self-excited vibration where the aerodynamic loading which sustains the motion is induced by the motion itself. Approaching

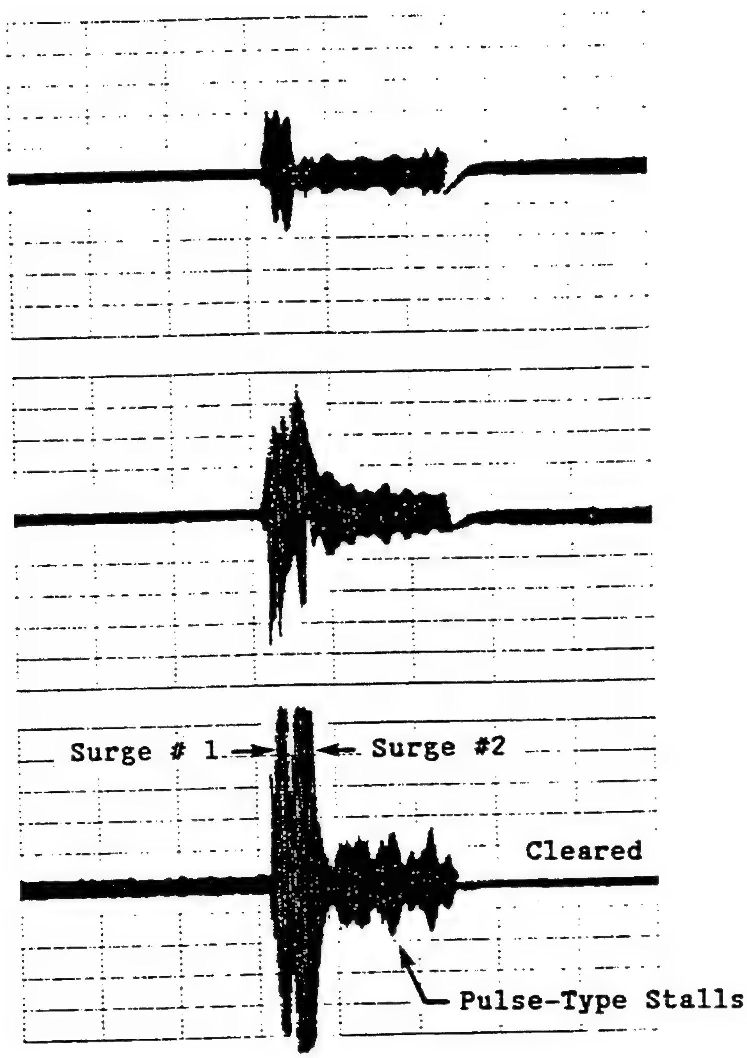


Figure 4.7. Pulse-Type Stalls and Surge in a Multi-Stage Compressor.

the instability, there is usually increasing SFV until the flutter boundary is reached. At that time, as shown in Figure 4.8, the modulating SFV becomes dominated by the flutter mode, a single sinusoidal response, usually in the 1F or 1T mode (instances of 2F mode flutter have been observed). Multiple mode flutter, although very rare, has also been seen. The blade stress, upon penetrating the flutter boundary, builds up very rapidly to a stabilized amplitude (the blade cannot extract anymore energy from the airstream), which may be appreciably in excess of scope limits. The amplitude will remain virtually constant until operating conditions are changed. This characteristic has led to the use of the term "limit-amplitude" flutter to describe the phenomenon. Figure 4.9 is the result of successive frequency analyses during a throttle to torsional stall flutter. Here, we can see that before the instability is developed, the frequency content of the signal is comprised of several modes, where at full instability, the vibratory response is at predominately one frequency which is a non-integer multiple of the rotor speed.

Instability may be encountered in a few blades of a stage or it may be a system instability where all the blades in the cascade vibrate at the same frequency and at a constant interblade phase angle, but not at the same amplitude. This is due to what is called blade mistuning, i.e., the blades are not identical. There are various types of flutter which may be encountered in a typical compressor. This includes stall flutter, choke flutter, and supersonic shock flutter. The location of these flutter regions is shown in Figure 4.10 and their characteristics are described below. Despite occurrences at different Mach number and flow regimes, the S/G signals of the three types of flutter are very similar. They are differentiated from one another by where they occur on the operating map.

4.3.1 Stall Flutter

Flutter occurring at high stage loading, as in a highly throttled stage, is called stall flutter. If it is at subsonic to transonic speeds, it is usually characterized by a torsional mode response and referred to as subsonic stall flutter. Supersonic stall flutter happens at subsonic to supersonic speeds and usually with a flexural mode response. These are positive incidence type phenomenon sensitive to stage loading, stage inlet pressure, and temperature and pressure ratio.

4.3.2 Supersonic Shock Flutter

Supersonic shock, or inviscid flow, flutter is pressure ratio dependent and occurs at supersonic speeds in the vicinity of the NOL. This type of flutter has been experienced in the development of high performance compressors. Generally, this type of flutter occurs in the 1T mode and precipitates at or near zero incidence angle.

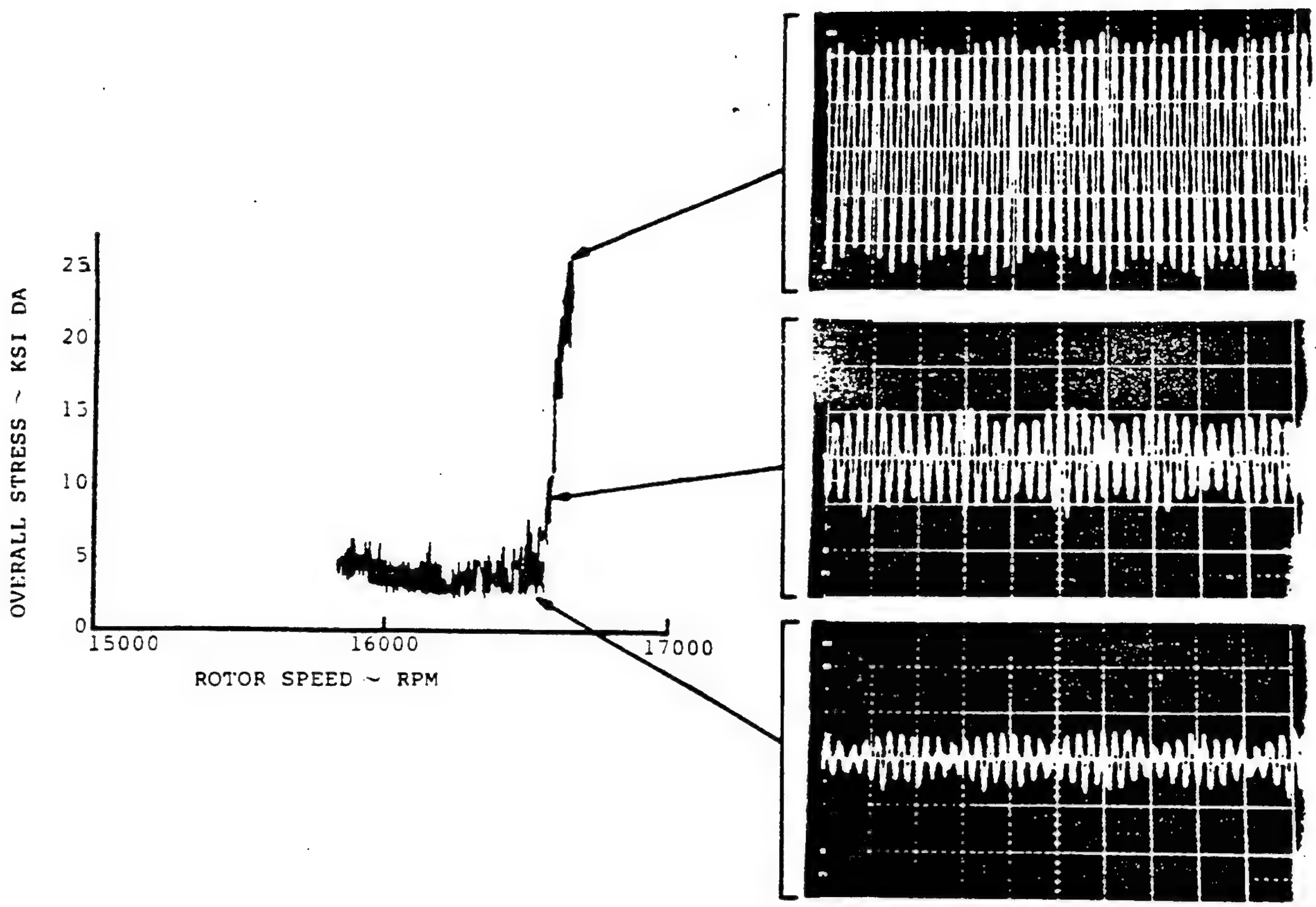


Figure 4.8. Typical Stress Waveforms Approaching Flutter Boundary.

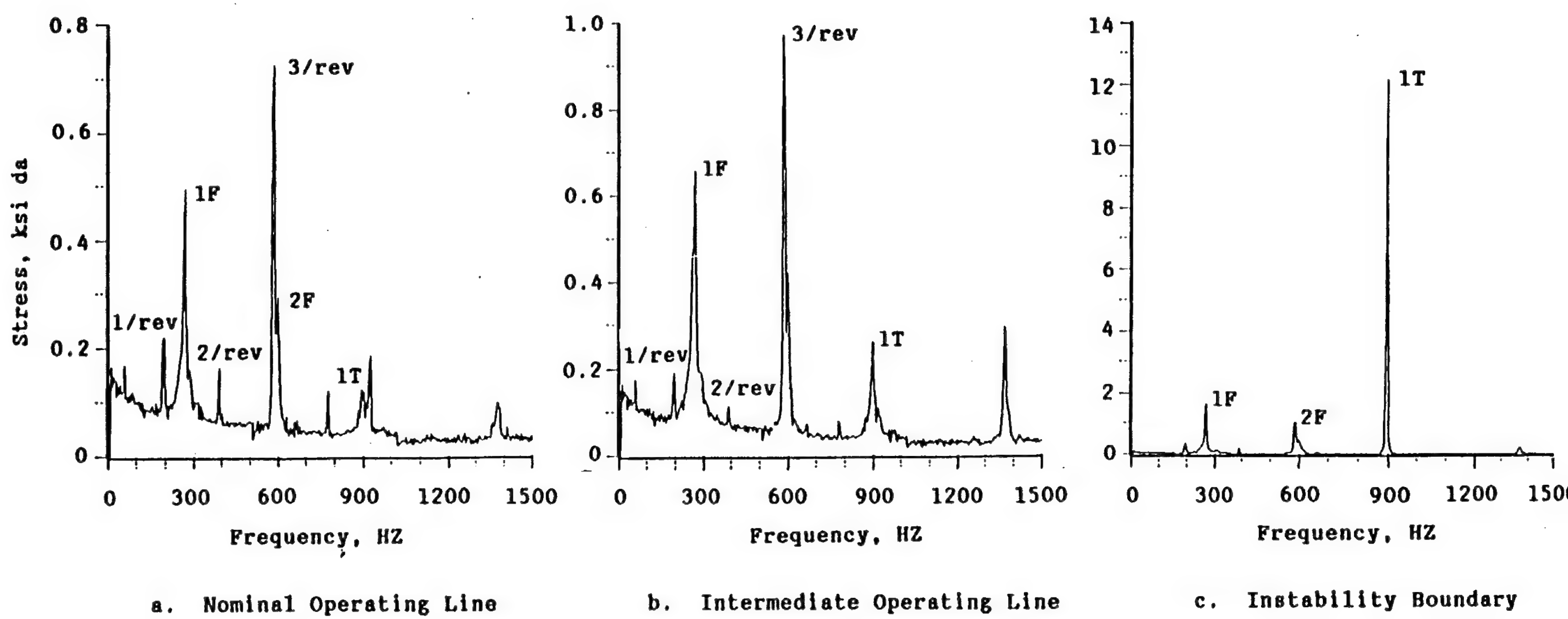


Figure 4.9. Frequency Analyses During a Throttle to Torsional Stall Flutter.

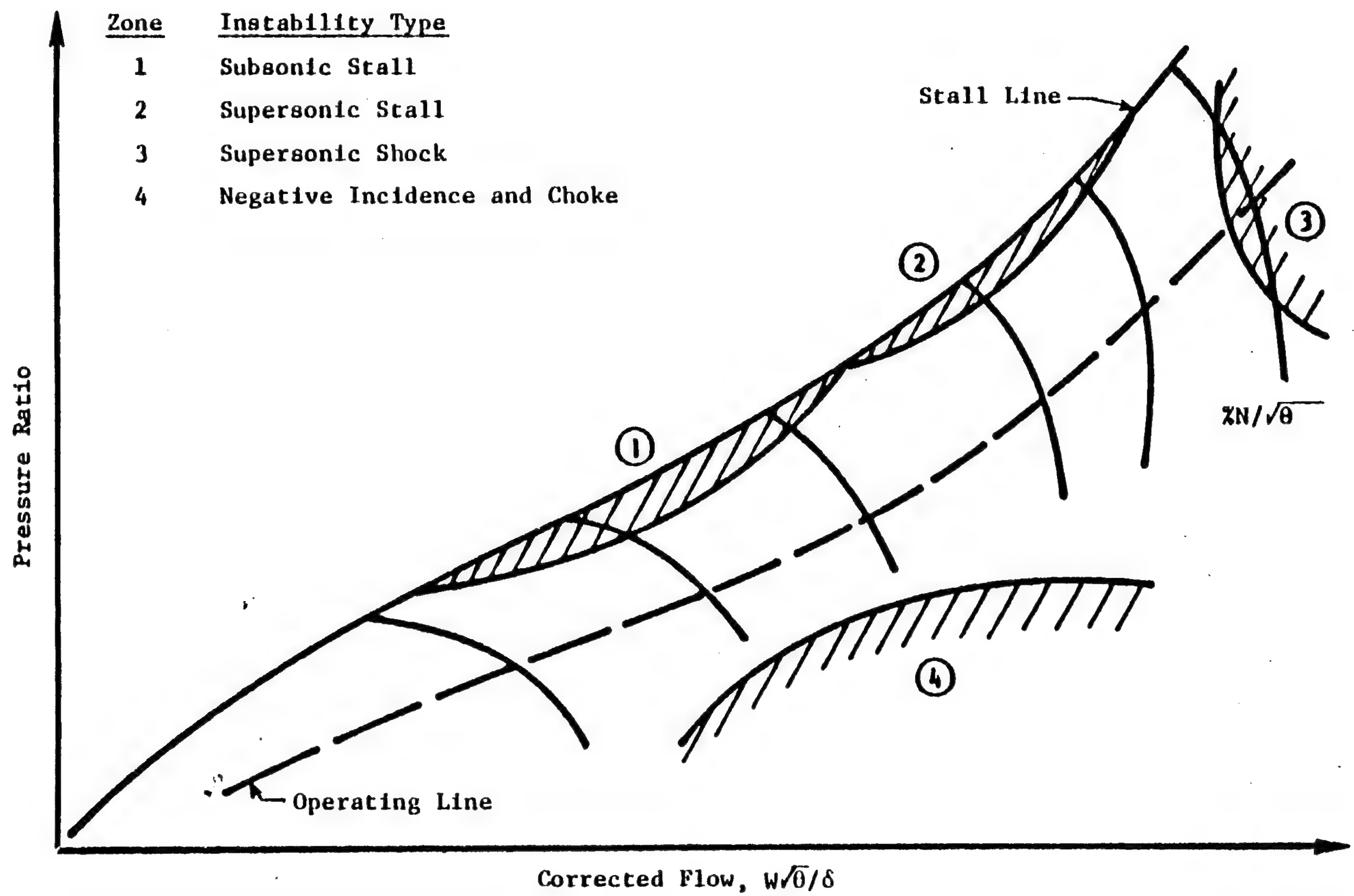


Figure 4.10. Typical Performance Map with Blade Flutter Zones.

4.3.3 Choke Flutter

Flutter that occurs at negative incidence and a low pressure ratio is called choke flutter. Choke flutter has been experienced at subsonic, transonic, and supersonic speeds and can manifest itself in the 1F, 1T, or 2F mode. This type of flutter usually occurs in the mid-stages of a compressor, especially when variable stator rows are involved.

4.4 INVALID SIGNALS

Interpretation of S/G signals can be made more difficult with the presence of erroneous signals from S/G's, electronic conditioning equipment, and the slip ring system. The identification of bad S/G signals has two basic goals: to preclude recording erroneous and misleading stress data, and to alert the A/M monitor to the need for remedial action. Accordingly, Figure 4.11 delineates typical bad signals, their possible causes, checks to be made, and some remedial actions. Figure 4.12 shows the time history and corresponding frequency spectrum for a noisy S/G.

4.4.1 Slip Ring Noise

The stresses in rotating blades are measured by S/G's whose signals are transmitted to the stationary oscilloscope displays and magnetic tape recorders. To convert from rotating sensors to fixed receivers, the S/G signals are transmitted through multichannel slip rings. Dirt, moisture, or defects in the contacts of the slip ring result in erroneous signals, as illustrated in Figure 4.13.

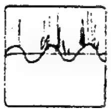
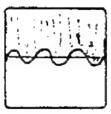
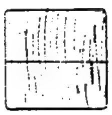
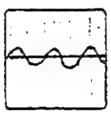
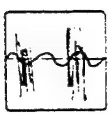
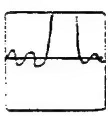
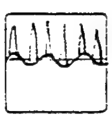
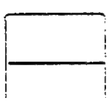
Symptoms	Possible Causes	Remedial Action
 On rotor blades: Noise at 1/rev, usually on one side of stress signal.	Slipring noise	* Try warming up rotor stack if noise is widespread. * Clean, or replace, the slipring if the noise persists.
 Constant noise on one side of stress signal.	Partially grounded circuit or slipring noise.	* Try reversing polarity of power supply - sometimes helps signal of grounded S/G's. * Clean, or replace, slipring. * Look for grounded exposed wires, plugs, or connections.
 All noise.	Grounded, shorted, or open circuit with intermittent grounding or shorting.	* Check for crosstalk from bad S/G. * Check for broken/damaged leads. * Check for slipring problems if several signals are lost in rapid succession.
 Signal visible through noise.	Crosstalk from bad gage in another circuit.	* Turn off power to bad gage, and ground its circuit if needed.
 Signal interrupted by noise frequently.	Intermittent ground or short.	* Check for damaged leads, and loose plugs or connections.
 Occasional loss of signal.	Intermittent opening or shorting.	* Check for broken wires in accessible areas. * Check slipring circuit, plugs, and connections for possible intermittency.
 Spikes on one side of signal.	Gage coming unbonded from blade or grid becoming over-stressed (yielding) during the tension portion of vibration.	* Invalid signal -- turn it off.
 No signal.	Open circuit. Power not turned on, malfunctioning amplifier, scope circuit, or other electronic problem.	* Check for broken wires or connections. * Check slipring for open circuit. * Make sure all electronic switches are in proper positions. * Check amplifier, scope, etc. for malfunction - put gage signal in another channel as a check.

Figure 4.11. Examples of Bad Stress Signals.

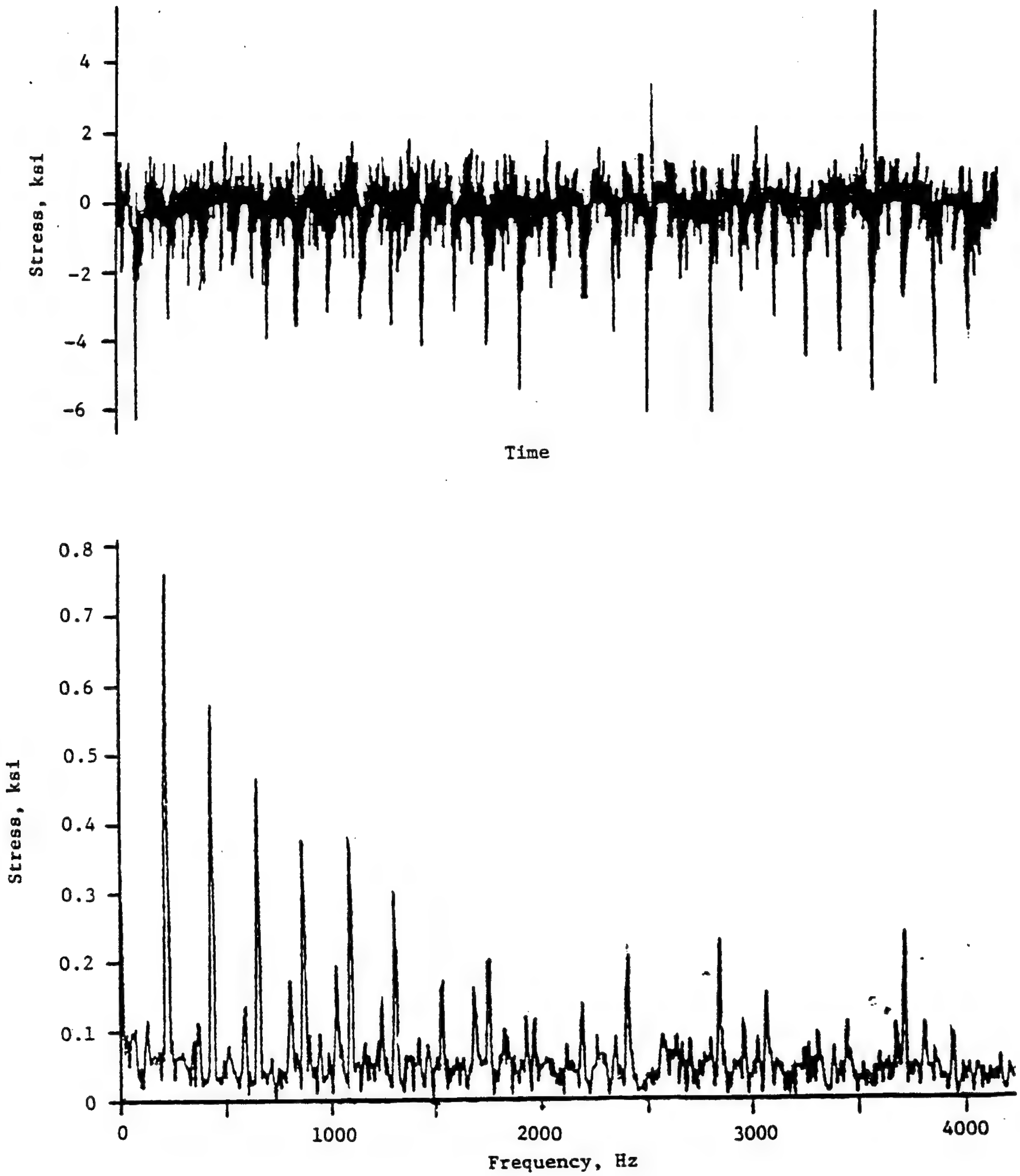


Figure 4.12. Stress Signal from a Noisy Strain Gage.

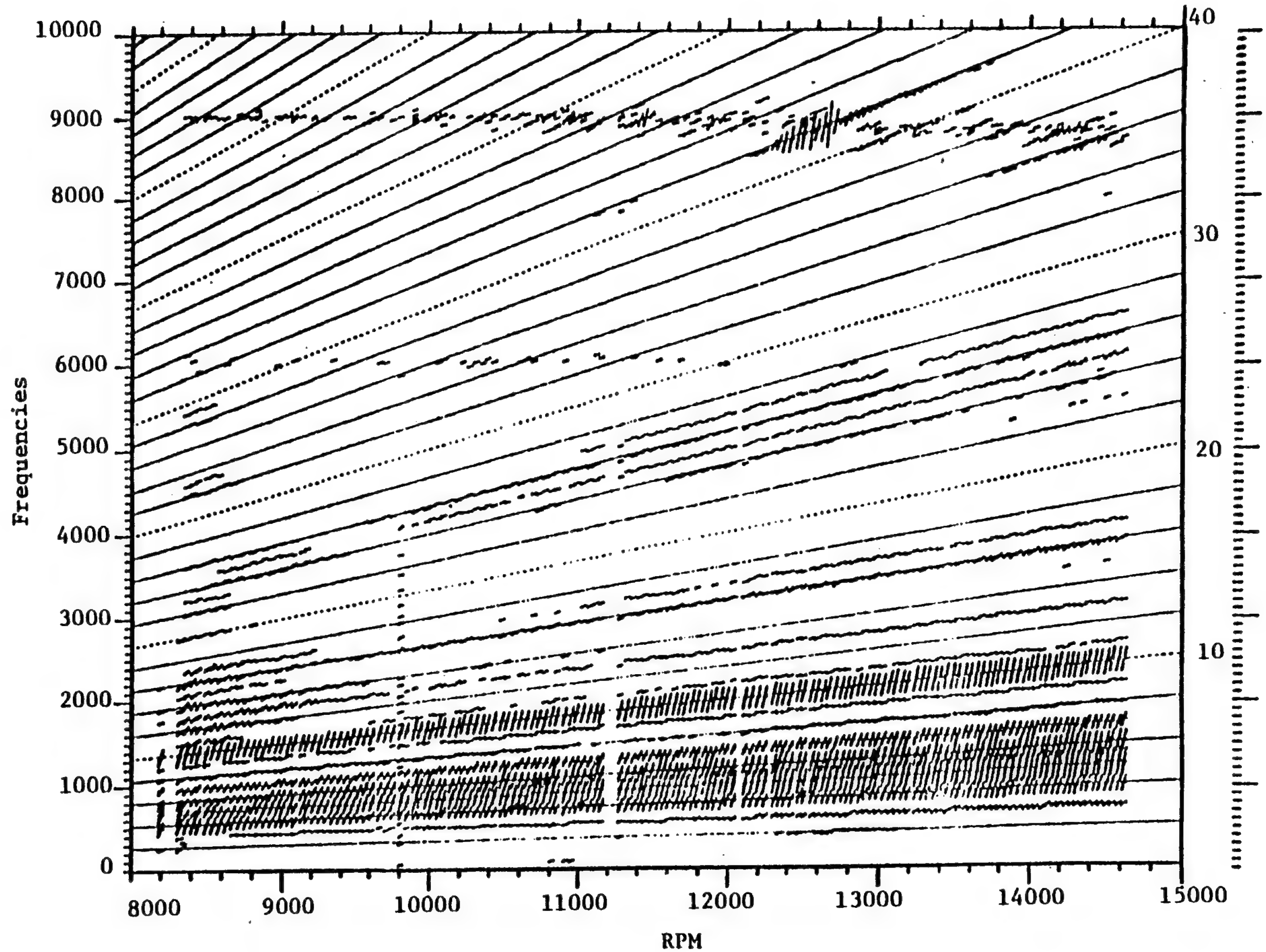


Figure 4.13. Campbell Diagram of a Strain Gage Signal with Slip Ring Noise.

5.0 REFERENCES

1. Baker, J.E., "Insights to Practical Applied Aeromechanics," General Electric T.M. No. 78-501, September 1978.

2. Cardinale, V.M., Bankhead, H.R., and McKay, R.A., "Experimental Verification of Turboblading Aeromechanics," Presented at the 56th Symposium of AGARD Propulsion and Energetics Panel, Turin, Italy, October 1980. Published in AGARD-CP-293, January 1986.

3. Fost, R.B., Gallardo, V.C., and Stowell, W.R., "Strain Gage Signal Interpretation," AFWAL-TR-85-2098, February 1986.

APPENDIX A

AEROMECHANICS STATION PROCEDURES

Collected herein are a bunch of different, sometimes unrelated, procedures for doing things in and around the A/M station. They are put here because they don't exist anywhere else, except in different people's memory.

A.1 REMOTE TAPE CONTROL

The nine permanent analog tape decks, 300-304 and 386-389, can be individually started and stopped from the A/M station during data acquisition. The remote tape control panel is located between A/M monitoring stations 2 and 3. To activate the remote tape control feature for a tape deck, the power must be first turned on by pressing the black panel button labeled "power." The green "ready" light on the panel should then light up, provided that the tape is threaded and ready to go. By pressing both the "run fwd" and "record" buttons at the same time, then releasing the run fwd button first, the tape recorder will begin recording data. To stop recording, simply press the "stop" button.

A.2 SWITCHING NETWORK

At each A/M monitoring station, the capability exists to switch any of the 36 scope signals to three different places by simply pressing a button. There are three buttons (red, white, and green) above each scope. Pressing one of these buttons over a particular scope directs that scope's display to the same colored BNC jack on the front of the monitoring station. These jacks can be hardwired to any of several ancillary A/M devices: e.g., the spectrum analyzer, voltmeter, function generator, or digital oscilloscope. Typically, we wire the red jack to the spectrum analyzer, the white jack to the digital oscilloscope, and the green jack is alternately wired to the function generator for the variable gain check (see Section A.3.1) and to the voltmeter for the sine wave check (see Section A.3.2). It should be noted that signals can be passed in either direction through the switching network as is the case for the variable gain check.

A.3 ANALOG END-TO-END CHECKS

An end-to-end check of a given data channel checks the calibration, if possible, of the channel and the channelization of its signal path between the test article and the A/M station. There are CRF Standard Procedures for calibration and channelization.

Calibration -- It would be nice to be able to re-calibrate each sensor and its data channel after installation in the CRF, but it's only possible for the sensors that are on the exterior of the compressor, e.g., Kulites and accelerometers. The best we can do for rotating sensors is to check the calibration at the slipring (we have to trust that the proper hookup to the slipring has been made). The remaining interior sensors are checked at the earliest connection outside of the compressor.

Channelization -- In channelization, the signal path of each sensor is checked to insure the properly amplified signal reaches its intended scope and tape recorder channel. This is done by inputting a known signal at the sensing end of the path (as close to the sensor as possible) and reading the output to the respective scope and tape recorder. Channelization insures that the routing, patchpanels, and processing equipment have been properly installed and are functioning correctly.

Audit -- After channelization, an independent audit of the sensor leadouts is made if time permits. The audit is made by a person other than the one who did the channelization. The audit deciphers the nomenclature attached to the sensor leads by the engine contractor and makes sure that their leadouts are connected to the proper CRF signal path.

A.4 OSCILLOSCOPES

Oscilloscopes, or scopes, are devices that display analog electrical signals from the various transducers in an amplitude versus time form. They are used to monitor all rapid transitory phenomena including stress, pressure, and vibration. One of the 144 scopes currently used in the CRF is shown in Figure A.1.

The trigger level control (bottom left), the variable sweep rate control (bottom center), and the adjacent three square switches (bottom right) control the timing and sweep rate of the electron pulse. The sweep rate is the speed at which the electron pulse moves across the scope screen creating the signal signature image. If the sweep rate is too slow, only a single pulse (dot) will appear on the screen, rather than the desired continuous signal. The three square switches are for making major adjustments (in powers of 10 seconds/grid division on the screen) while the variable sweep rate control and the trigger level control are for finer sweep adjustments.

The scope can be changed from an internal to an external trigger by the switch above the trigger level control. If the scope is internally triggered, then the moment that each electron pulse starts across the screen is determined by a beat produced in the scope. This is used for calibration signals when no external trigger is available. In the CRF, the A/M scopes are externally triggered by a 1/rev signal from the drive system. The 1/rev is input at the bottom right-center of the scope. With a 1/rev trigger the sweep rate is proportional to the rotating speed of the test article. Signals on externally 1/rev triggered scopes will thus appear

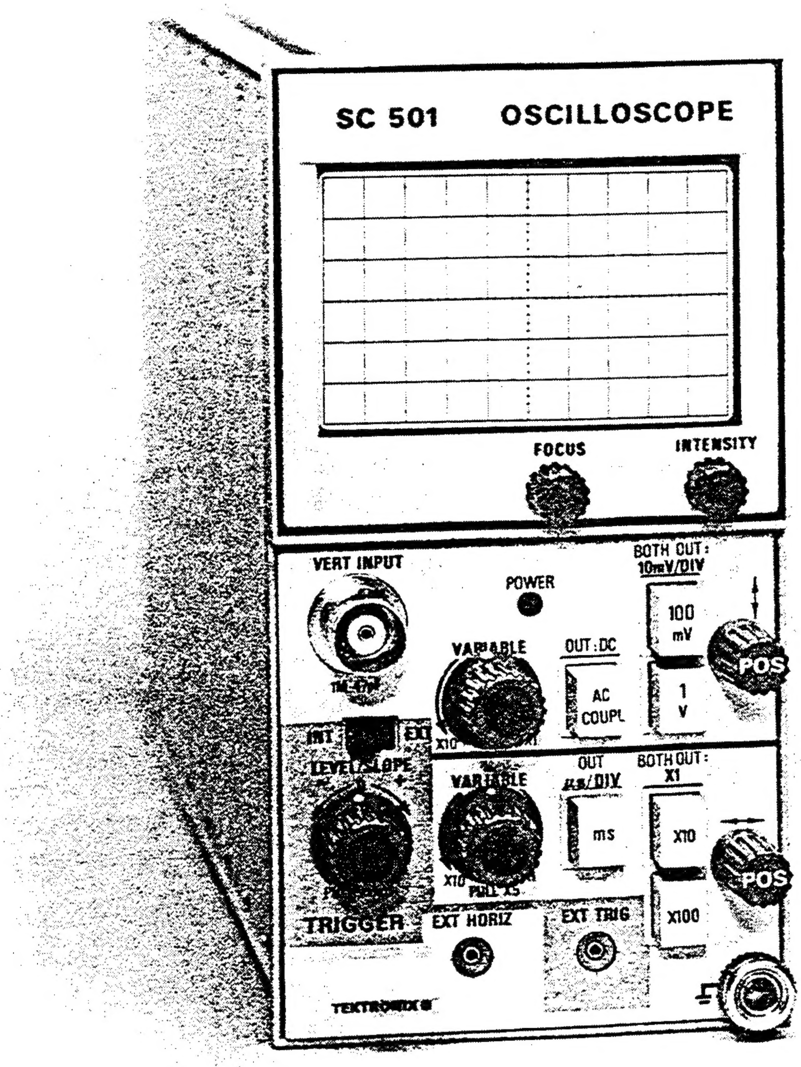


Figure A.1. CRF Oscilloscope.

horizontally motionless if their components are integral engine orders, like resonant vibration, regardless of the sweep setting.

A.4.1 Variable Gain Check

The purpose of the variable gain check is to calibrate each scope so that one vertical division represents a desired number of engineering units (e.g., ksi or mils). Because the scope calibration may drift, the variable gain check must be performed before each run. To facilitate this, a physical mark can be made over the dot on the vertical variable dial, see Figure A.1, so now this alignment can be more easily checked before each run. The main reason to check this calibration comes from the possibility of the variable dial being inadvertently moved while making other adjustments on the face of the scope.

Generally, the S/G scopes are calibrated for 5 ksi per major division and the amplifiers are set so that each ksi equals 125 mVsa (0-peak). Recall that 1.0 mVsa equals 0.707 mV rms. Then the corresponding voltmeter reading for the above 5 ksisa signal will be 442 mV rms (because 5 ksisa x 125 mVsa x 0.707 mV rms = 442 mV rms). This is the basis of the variable gain check for S/G's.

Prior to the variable gain check we need to disengage the A/M patch panel to keep the function generator signal from feeding back into the signal conditioning amplifiers. To do a variable gain check for a S/G, we first set up the function generator (located uppermost on the right-hand side of each A/M monitor station) to send a 1000 Hz sine wave signal to the scope. Then we adjust the function generator until the voltmeter reads 442 mV rms. Next we move the variable gain control on the scope until the sine wave peak-to-peak amplitude is two vertical divisions on the screen. The scope is now calibrated for 5 ksisa per screen division or 30 ksida full scale. Finally, for future reference, as mentioned above, it is convenient to put a mark on the scope over the white dot on the variable gain control.

Vibration scopes are calibrated following the above procedure, but now we are using a mil displacement scale (the accelerometer signal has been integrated twice before being displayed on the scope). If we want, say, 5 mils/division on the scope, then the appropriate volt meter reading would be 500 mV since the sensitivity of the vibration system is 100 mV rms/mil sa.

A.4.2 Oscilloscope Sine Wave Check

The sine wave (could be a square wave) check consists of sending a sine wave from the signal conditioning room through the amplifiers and A/M patch panel to each scope. This insures that the amplifiers, patch panel, and scopes are set and functioning properly and consistently. It also indicates if the amplifiers have "drifted" or malfunctioned since the last check. The sine wave check is performed at the beginning and end of each run as indicated in the A/M station checklist in Figure 3.5.

After the sine wave signal appears on the scopes, the A/M monitor records the voltage readings in the daily log sheet. To do this, he connects each scope to the voltmeter and obtains the AC RMS voltage. These values are compared to those from the previous sine wave check. Readings may drift from run to run, but if they all drift the same, this is OK. However, the readings should not drift from start to end of a run. If this does happen, the recorded data on all channels whose sine wave voltage has shifted becomes suspect.

Note:
- The patch panel must be engaged during the sine wave check.
- The SGMS should be off-line during the sine wave check as all channels will be over limits.
- DO NOT adjust the vertical variable gain dial during this check as this will alter the calibration of the scope.

A.5 SPECTRUM ANALYZER SETUP

In this section we would like to discuss how to setup the spectrum analyzers before each CRF test run. This is, of course, after we have read the Operator's Manual and found out to basically set up the analyzer with things like: 5 volts peak-to-peak, a Hanning FFT weighting window, split screen with real time display in the upper and peak hold in the lower, etc., etc. Now, before the run, press the logo on the front panel. To set the proper engineering units on the vertical scale, press the following front panel buttons:

1. <MV/EU>
2. <RECALL>
3. <ENTER>

At <RECALL> the millivolts/engineering units scale will appear in the upper right-hand corner of the monitor screen. With the standard setup in the CRF, mV/eu = 141.0 for accelerometers and = 125.0 for S/G's. If the proper value doesn't appear, it can be entered using the front panel buttons.

During the run, it is convenient to have an ID number on the screen because all four of the analyzers can print to the printer. This way, we at least know from which A/M monitoring station the print originated. To set the analyzer ID number, press the following front panel buttons:

1.	<SEL>	(under PRGM) select a menu
2.	<2,3>	turns on the ID Block Menu
3.	<3>	modify menu
4.	<OPER>	the ID appears in upper left-hand screen corner
5.	<#>	enter the station ID: 1, 2, 3, or 4
6.	<SEL>	(under PRGM) select a menu
7.	<2,3>	turn on the ID Block Menu
8.	<2>	permanently turn on the ID block
9.	<OPER>	

A word of caution about the vertical scale. For S/G's, with mV/eu = 125.0, the EU vertical scale will be 0-20 ksida. To change this scale, do not use the volts buttons (the scale will indeed change, but the engineering units are no longer correct). Instead, use the Y-GAIN buttons to change the EU scale, leaving the peak-to-peak voltage level alone.